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PHYSIOLOGICAL EVALUATION OF CHEMICAL PROTECTIVE CLOTHING

DEPARTMENT OF THE NAVY
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Navy Clothing and Textile Research Facility (NCTRF) physiologists evaluated chemical warfare (CW) protective clothing ensembles worn by 8 volunteers working (170 W/m²) for 3 hours in up to 5 different environments, consisting of a control (22.2°C/50% r.h.), and a warm humid (29.4°C/45% r.h.), a hot humid (...°C/60% r.h.) with and without a 4.5 m/sec wind, and a hot dry (48.9°C/20% r.h.) climate. The evaluated uniforms were the British Mark III, two-piece, permeable outfit and the Norwegian Helly-Hansen, one-piece, semi-permeable garment.

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The Mark III was evaluated alone, with the wet-weather (WW) gear over it to make the CW garment impermeable, and finally with a wettable cover (WC) over the WW to alleviate some of the thermal stress. All CW clothing ensembles consisted of the standard Navy utility uniform (chambray shirt and denim trousers), CW uniform, standard U.S. Army butyl boots and gloves, and Navy Mark V mask. For baseline data, the utility uniform, utility + WW, and utility + WW + WC, all with the Mark V mask, were also evaluated in the different environments. (U)

At 22.2°C, all individuals easily completed 3 hours of work in the 7 different ensembles. In the 29.4°C environment, however, tolerance time (TT) was reduced by 27% and 49% for the Norwegian and the Mark III + WW, respectively. At 35°C, with no wind, TT of the Mark III was 69% of the utility uniform alone. Further reductions in TT of 66% and 75% compared with the control were evident for the Norwegian and the Mark III + WW, respectively. The WC over the Mark III and WW had the effect of increasing TT by almost 90%; however, TT did not reach the level observed with the Mark III alone. Testing of the Norwegian and Mark III uniforms in the 4.5 m/sec wind had the effect of increasing TT 48% and 27%, respectively, compared with 35°C environment without the wind. When the Mark III was evaluated at 48.9°C, TT was only 38% of that observed with the utility uniform alone. (U)

This study revealed the following:

1) the least stressful CW ensemble was the Mark III with no overgarment;
2) the Norwegian and Mark III + WW uniforms were the most stressful and created almost identical thermal stress, except for lower skin temperatures and higher evaporation rates with the Norwegian uniforms; and
3) heat stress can be somewhat alleviated, and tolerance time thereby increased, with the use of an outer wettable cover over impermeable CW garments. (U)

TABLE OF CONTENTS

	Page
List of Illustrations	iv
List of Tables	vi
Introduction	1
Background	2
Test Plan	3
Methods and Procedures	3
Results	7
Tolerance Time	7
Heart Rate	7
Rectal Temperature	9
Mean Weighted Skin Temperature	11
Rectal-to-Mean Skin Temperature Gradient	12
Sweat and Evaporation Rates	12
Subjective Comments	14
Discussion	15
Conclusions	20
Acknowledgements	21
Appendix A. Description of Chemical Protective Clothing	A-1
Appendix B. Illustrations	B-1

LIST OF ILLUSTRATIONS

Figure		Page
1	Tolerance times for each clothing-environment combination.........	B-2
2	Half-hourly heart rate values for each clothing ensemble tested at 22.2°C..	B-3
3	Half-hourly heart rate values for each clothing ensemble tested at 29.4°C..	B-4
4	Half-hourly heart rate values for each clothing ensemble tested at 35°C, without wind..	B-5
5	Half-hourly heart rate values for each clothing ensemble tested at 35°C, without and with wind.................................	B-6
6	Half-hourly heart rate values for each clothing ensemble tested at 48.9°C..	B-7
7	Half-hourly rectal temperature values for each clothing ensemble tested at 22.2°C...	B-8
8	Half-hourly rectal temperature values for each clothing ensemble tested at 29.4°C...	B-9
9	Half-hourly rectal temperature values for each clothing ensemble tested at 35°C, without wind.............................	B-10
10	Half-hourly rectal temperature values for each clothing ensemble tested at 48.9°C...	B-11
11	Half-hourly mean skin temperature values for each clothing ensemble tested at 22.2°C...	B-12
12	Half-hourly mean skin temperature values for each clothing ensemble tested at 29.4°C...	B-13
13	Half-hourly mean skin temperature values for each clothing ensemble tested at 35°C, without wind.............................	B-14
14	Half-hourly mean skin temperature values for each clothing ensemble tested at 35°C, without and with wind....................	B-15
15	Half-hourly mean skin temperature values for each clothing ensemble tested at 48.9°C...	B-16
16	Rates of sweat (SR) and evaporation (EVAP) for each clothing ensemble tested at 22.2°C...	B-17

LIST OF ILLUSTRATIONS (cont'd)

Figures		Page
17	Rates of sweat (SR) and evaporation (EVAP) for each clothing ensemble tested at 29.4°C	B-18
18	Rates of sweat (SR) and evaporation (EVAP) for each clothing ensemble tested at 35°C, without and with wind	B-19
19	Rates of sweat (SR) and evaporation (EVAP) for each clothing ensemble tested at 48.9°C	B-20
20	Mark III chemical protective uniform	B-21
21	Norwegian Helly-Hansen chemical protective uniform	B-22

LIST OF TABLES

Table		Page
I	Environmental conditions for testing CW garments	4
II	Rate of rise (mean $\pm$ S.E.) of rectal temperature (°C/h) for each clothing-environment combination	10
III	Final rectal-to-skin temperature gradients (mean $\pm$ S.E.) for each clothing-environment combination	13
IV	Efficiency of sweating (evaporation-to-sweat rate ratio) for all environment-clothing combinations except those in which the WC was added to the ensembles (see text)	17
V	Rates of heat storage (in W) for wet weather (WW) and wettable cover (WC) ensembles	19

PHYSIOLOGICAL EVALUATION OF
CHEMICAL PROTECTIVE CLOTHING

INTRODUCTION

The purpose of this study was to determine the heat stress on individuals working in hot environments while wearing chemical protective clothing. The lightweight, permeable, charcoal-layered, two-piece, British Mark III suit was compared with the semi-permeable, Norwegian Helly-Hansen uniform in up to 5 different environments--a comfortable (22.2°C, 50% r.h.), a warm humid (29.4°C, 45% r.h.), a hot humid (35.0°C, 60% r.h.), with and without a 4.5 m/sec wind, and a hot dry (48.9°C, 20% r.h.) environment. Further tests were undertaken to determine the physiological strain imposed by wearing the impermeable wet-weather gear over the uniforms, and the possible decrease of the heat stress by using a wettable cover over the other layers (that is, standard utility uniform plus Mark III plus wet-weather gear). Based on the results of these tests, it was determined that, while impermeable chemical protective clothing was worn, heat stress became a serious problem at moderate environmental conditions (29.4°C, 45% r.h.), with tolerance times diminishing as much as 49% compared with the comfortable climate. The addition of wind had the effect of increasing tolerance time as did the addition of the wettable cover to the impermeable garments. This report provides some background into the problems encountered when chemical protective clothing is worn under adverse conditions and details the methodology employed and the physiological responses of 8 men wearing 7 combinations of chemical protective clothing in up to 5 different environments.

BACKGROUND

Chemical warfare (CW) protective clothing achieves its protection by isolating the wearer from a toxic environment. However, by virtue of its isolative qualities, CW clothing also reduces the ability of the wearer to lose heat, both through the increase in thermal insulation due to the thickness of the clothing ensemble, and through the impedance of free evaporation from the skin surface. Studies have demonstrated that men wearing CW clothing cannot work for extended periods of time in hot environments (1,2). Men working in clothing which is totally impermeable to water vapor transfer have been able to work safely at moderate levels for about 1 hour at 27° to 30°C, but for less than 30 minutes when ambient temperature is greater than 32°C (3). Wearers of clothing systems which permit some evaporation of sweat have been shown to have extended tolerance times compared with those wearing impermeable suits (4). It has been calculated that men working at ~330 watts at 35°C, 50% r.h. will be able to work from 2.5 to 5.5 hours (depending upon type of permeable CW clothing worn) before the 50% casualty level is reached (5).

Personnel serving topside aboard ship are faced with additional problems in a chemical environment, namely, spraying of water and operating within exposed areas. Current Navy policy dictates that shipboard personnel operating topside wear the neoprene-coated, wet-weather ensemble over the CW garment, which in effect, would make the whole system impermeable to water vapor, and hence would increase the heat stress on personnel wearing these outfits.

Various approaches for reducing the heat stress in chemical protective clothing have been undertaken. Included are: 1) methods to further increase the water vapor permeability of the clothing; 2) use of battery-operated back-packs to deliver filtered air or water into an otherwise impermeable clothing system, thus increasing either evaporative and convective or conductive cooling; and 3) use of a wettable cover over an impermeable garment, which could increase heat dissipation by evaporation of water from the wet cover. A wettable cover could prove to be a reasonable method in Naval operations because of the large, readily available source of water. A mathematical model on the practical use of a wettable cover to reduce heat stress has demonstrated increased heat losses from the skin of 40 and 200 watts at environments of 35°C, 70% r.h. and 50°C, 20% r.h., respectively (6).

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TEST PLAN

In order to determine the heat stress imposed while CW protective clothing was worn in hot environments. various configurations of CW clothing were tested in a control, a hot-dry, a warm- and a hot-humid environment. Testing in the standard Navy utility clothing served as a reference for the heat strain induced under these climatic conditions. Additional layers of clothing were then donned in sequence for successive trials in the same environments.

METHODS AND PROCEDURES

Eight men, who were deemed physically fit and had had no previous heat-related injuries, were selected for participation in this study during the summer months. After having the nature of the study and possible risks explained, they consented to participate. The mean ± S.D. physical characteristics of the subjects were: age, 24.6 ± 3.9 years; height, 174.1 ± 9.5 cm; weight, 78.2 ± 8.1 kg; and surface area, 1.93 ± 0.14 m^2.

All subjects were first familiarized with the test equipment and were then concurrently heat acclimated by 5 consecutive days of work in the heat for 2 hours per day. Each hour of exposure consisted of two cycles of 25 minutes of walking at 1.56 m/sec, 0% grade and 5 minutes of sitting. By alternation of the exposures to humid (37.8°C = 100°F, 70% r.h.) and dry (48.9°C = 120°F, 20% r.h.) heat, acclimation to both high- and low-humidity environments could be achieved. Subjects were acclimated while wearing the standard utility clothing and the Navy Mark V gas mask. The gas mask was worn to familiarize the individual with its use before the experimental sessions began.

Following the acclimation procedure, the subjects underwent a series of experimental trials while wearing varying configurations of CW protective clothing. Seven different ensembles were evaluated in up to five different environments. Environmental conditions, which are described in Table I, consisted of a control (A in table), a warm humid (B), a hot humid with and without a 4.5 m/sec wind (C&D), and a hot dry climate (E).

The ensembles, which were evaluated in a random manner, included the following:

1. Control (wt = 2.07 kg)
    a. standard Navy utility uniform, consisting of chambray shirt and denim trousers (MIL-S-87060 and MIL-T-87062)
    b. underwear
    c. shoes, socks
2. Standard Navy wet-weather-gear ensemble (wt = 3.67 kg)
    a. all of 1
    b. two-piece Navy foul-weather gear, including attached hood (MIL-P-82277 and MIL-O-22776)
3. Wettable cover ensemble (wt = 4.71 kg)
    a. all of 2
    b. three-piece, cotton-type outer garment, including hood, smock and trousers (MIL-S-12227 and MIL-L-12226)

Table I. Environmental conditions for testing CW garments

Test Environment	T_{db} °C (°F)	T_{wb} °C (°F)	r.h. %	v m/sec (mph)	WBGT °C (°F)
A	22.2 (72)	15.5 (59.9)	50	1.19 (2.6)	1.75 (63.5)
B	29.4 (85)	21.0 (69.8)	45	1.19 (2.6)	23.6 (74.4)
C	35.0 (95)	28.3 (82.9)	60	1.19 (2.6)	30.3 (86.6)
* D	35.0 (95)	28.3 (82.9)	60	4.47 (10)	30.3 (86.6)
E	48.9 (120)	28.0 (82.4)	20	1.19 (2.6)	34.3 (93.7)

* Only for Mark III and Norwegian ensembles

4. Mark III ensemble (wt = 4.78 kg). (Refer to Appendix A for garment description.)

   a. all of 1
   b. two-piece chemical protective overgarment, including smock with attached hood and trousers
   c. butyl gloves with cotton liners (MIL-G-12223)
   d. butyl footwear covers (MIL-F-12224)

5. Wet-weather gear over Mark III ensemble (wt = 6.38 kg)

   a. all of 4
   b. standard Navy two-piece foul-weather garment

6. Wettable cover over Mark III and wet-weather-gear ensemble (wt = 7.42 kg)

   a. all of 5
   b. three-piece wettable-cover ensemble

7. Norwegian (Helly-Hansen) ensemble (wt = 5.38 kg). (Refer to Appendix A for garment description.)

   a. all of 1
   b. one-piece chemical protective overgarment with attached hood
   c. butyl gloves with cotton liners
   d. butyl footwear covers

All ensembles also included the Navy Mark V gas mask.

Ensemble 1 was evaluated in all test environmen s except (D), while ensemble 4 was evaluated in the five environments. The remaining configurations were worn only in environments A through C, with the exception of the Norwegian suit which was also evaluated under the high wind velocity (4.5 m/sec) environment (D). Each exposure consisted of walking on a level treadmill at 1.34 m/sec for 25 minutes followed by 5 minutes of rest; this cycle was repeated until 3 hours had elapsed. The mean metabolic rate at this work level was $\sim$170 W/m^2 (0.95 L/min = 282 kcal/h).

During all heat exposures, the individual was continuously monitored for deep body and skin temperatures. Rectal temperature (T_{re}) was measured with a Y.S.I. thermistor probe inserted 10 cm beyond the anal sphincter. Skin temperature was measured with copper-constantan thermocouples attached to the chest, forearm, and calf. Mean skin temperature ($\bar{T}_{sk}$) was then determined according to Burton (7). Heart rate was measured with an ECG counted every 10 minutes. Sweat and evaporation rates were determined by changes in nude and clothed body weights, respectively, after adjustment for water intake. The Mark V gas mask was modified somewhat with a Tygon tube inserted into the mouthpiece for water intake. Water replacement was strongly encouraged to prevent dehydration effects from taking place.

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When the wettable cover was evaluated over the wet-weather gear, the following procedure was utilized. The individual was weighed dry, sprayed with water until the garment was saturated, and then reweighed to determine the amount of water which was taken up by the garment. At the end of the 25-minute exercise period, the weight of the subject was measured prior to his being resprayed with water. Total evaporation rates were then calculated by determining the change in body weight during each of the walking periods, summing these values, and then correcting for water intake.

Heat exposures were planned to be 3 hours in duration. However, the test was terminated if any of the following occurred: rectal temperature >39.5°C or 39.2°C during work or rest, respectively; HR >180 or 140 beats per minute during work or rest, respectively; rectal-skin temperature crossover; nausea, syncope, dry skin, headache; subjective distress of the subject.

All variables were analyzed with a two-way (clothing x environment) ANOVA. Tukey's multiple comparison test was used as a follow-up if significant ($p<0.05$) F-values were found.

RESULTS

Tolerance Time

A summary of the mean time the subjects tolerated the clothing-environment combinations is presented in Figure 1. All individuals, regardless of clothing ensemble, were able to tolerate the 22.2°C exposure for the full 3 hours. At 29.4°C the mean tolerance time for the utility, utility + wet weather (WW), and utility + WW + wettable cover (WC) was 180 min. However, when the Norwegian suit was tested, tolerance time decreased to 134 min and was significantly less than the 180 min found with the Mark III uniform. When the WW gear was added to the Mark III, tolerance time was reduced to 93 min, which was a significant reduction from the time observed with the Mark III alone. However the addition of the WC over the Mark III + WW increased the tolerance time back to that observed when no foul-weather gear was worn.

At 35°C, the individuals were able to maintain thermal equilibrium for up to 3 hours when the utility uniform was worn alone. With the addition of the impermeable WW covering, tolerance time was significantly reduced to 107 min. The WC over the WW gear increased the tolerance time of the individual by 50 min. When the Norwegian uniform was worn, tolerance time was significantly reduced (to 62 min) compared with both the utility uniform control and the Norwegian uniform at 29.4°C. The mean tolerance time for the Mark III alone at 35°C was 124 min compared with 45 min with the addition of the WW gear. The WC added to the ensemble improved the mean tolerance time to 85 min.

The Mark III and Norwegian ensembles were evaluated at 35°C, 60% rh with a 4.5 m/sec (10 mph) wind. The mean tolerance time with the Mark III suit increased 33 min (from 124 to 157 min) with the addition of the high wind. Individuals wearing the Norwegian uniform exhibited a similar improvement in tolerance time, from 62 to 92 min, when evaluation was conducted with the 4.5 m/sec wind.

Only the utility uniform and Mark III ensemble were tested at 48.9°C. All individuals easily tolerated this environment for three hours while wearing the utility uniform; however, tolerance time while wearing the Mark III was only about one third of that baseline value (68 min).

Heart Rate

The heart rates (HR) for each clothing ensemble in the different environments are presented in Figures 2-6. At 22.2°C (Figure 2), the HR's after 180 min of exposure were similar (∿100 beats per minute) for the utility uniform alone, with the WW gear and with the WW + WC. When the Mark III was worn, final HR was slightly, but not significantly, higher (108 beats/min) than the 22.2°C exposure with the utility uniform alone. The addition of the WW gear to the Mark III, however, increased the final HR to 132 beats/min, which was significantly higher than the final HR for both the utility alone and the Mark III alone. When the WC was then added to the Mark III + WW, final HR was found to decrease to 114 beats/min, which was not significantly higher than the Mark III alone but was higher than the control (utility uniform) exposure ($p<0.05$). Final HR with the Norwegian suit was 120 beats/min, which was significantly lower than the Mark III + WW and significantly higher than the Mark III alone. There was no significant difference between the Norwegian suit and the Mark III + WW + WC.

As seen in Figure 3, the 29.4°C exposures produced a similar gradation of HR responses depending upon the ensembles tested. Final HR for the utility uniform alone and with the WW + WC was similar at ∿100 beats/min. However, when the WW gear alone was worn over the utility uniform, final HR was significantly increased over the control exposure to 115 beats/min. Final HR for the Mark III alone was 123 beats/min, which was significately elevated compared with the control exposure. With the WW gear added to the Mark III, tolerance time, as previously noted, was reduced; and final HR was significantly increased (145 beats/min) compared with both the control exposure and the Mark III alone. Further addition of the WC to the ensemble resulted in a significant reduction of the final HR to 135 beats/min, which was still significantly higher than the final HR found with the Mark III alone. Individuals wearing the Norwegian suit were found to have final HR's similar to those observed with the Mark III + WW. At 90 min, the time at which at least half of the test subjects were still walking, final HR was 142 beats/min, which was similar to that observed at 90 min for the Mark III + WW gear.

For the 35°C condition without the 4.5 m/sec wind, tolerance times were reduced in all clothing ensembles except for the utility uniform, as noted above. In order to make comparisions of HR among the various configurations, the 60-min value was used as the "final" HR for this exposure. As seen in Figure 4, the HR at 60 min for the control (utility uniform) was ∿100 beats/min, which was similar to the HR found in the 22.2°C and 29.4°C environments. The HR during this condition, however, continued to rise throughout the 180 min, so that the 180-min HR was 110 beats/min. When the WW gear was added to the utility uniform, final HR (at 60 min) was significantly increased to 147 beats/min. Addition of the WC over the WW resulted in a HR at 60 min of 123 beats/min, which was significantly lower than the 60-min value for the WW gear alone, but higher than the control value. At 60 min, the mean HR for the Mark III uniform was 141 beats/min. Adding the WW gear resulted in both a reduction in tolerance time (Figure 1) and an increase in HR (158 beats/min at 40 min). The WC over the WW gear caused a significant reduction in HR, such that the 40- and 60-min HR's were 142 and 150 beats/min, respectively. While the Norwegian uniform, was worn, the mean HR at 60 min was 150 beats/min, while the value at 40 min was 143 beats/min. The 40- and 60-min HR values with the Norwegian and Mark III + WW + WC were similar.

Figure 5 demonstrates the effect the 4.5 m/sec wind had on the HR response while either the Mark III or the Norwegian uniform was worn at 35°C. As noted in Figure 1, tolerance time was increased significantly when testing was conducted in a high wind. Again, with the 60-min time period as a reference, it is seen that the HR was reduced 9 beats/min with the Mark III but remained the same with the Norwegian ($p<0.05$).

At 48.9°C (Figure 6), the final HR of 127 beats/min for the utility uniform was significantly higher than the values obtained in the other 3 ambient temperatures. Individuals tested with the Mark III had a significantly reduced tolerance time (Fig. 1) and a significantly elevated HR. With the 50-min value as a reference, the mean HR with the Mark III was 155 beats/min compared with a value of 110 beats/min for the control.

Rectal Temperature

The mean rectal temperatures for the 8 subjects exercising in the different environments in the 7 clothing ensembles are presented in Figures 7 through 10. For the control at 22.2°C (Figure 7), T_{re} leveled off in all ensembles; the degree of elevation, however, depended upon the clothing ensemble worn. With the utility uniform alone, final T_{re} was 37.50°C compared with the final T_{re} of 38.00°C while the Mark III + WW ensemble was worn ($p<0.05$).

As seen in Figure 8, at 29.4°C the final values of T_{re} with the utility uniform alone and with utility + WW + WC ensemble were no different from those values observed at 22.2°C. However, while the relative ranking of the ensembles remained the same as in 22.2°C, the five remaining emsembles produced final T_{re}'s which were significantly higher in the 29.4°C environment. At 90 min, the last time period in which a representative sample of individuals wearing the ensembles was still in the chamber, the "final" T_{re} for the utility uniform alone, the utility + WW, and the utility + WW + WC were 37.50°, 37.83° and 37.71°C, respectively. Exposures with the Mark III alone produced a mean T_{re} of 37.90°C at 90 min. With the addition of the WW, the 90-min T_{re} was increased significantly to 38.62°C compared with 38.12°C when the WC was added to the latter ensemble. When the individuals wore the Norwegian ensemble, the mean 90-min T_{re} was 38.49°C, which was not statistically different from the Mark 3 + WW combination.

As noted in the HR section, tolerance times at ambient temperatures >29.4°C were significantly reduced from those observed at the less stressful environments. Hence, the 50- and 60-min time periods were evaluated for T_{re} responses in the 35° and 48.9°C environments, respectively. Figure 9 depicts the mean T_{re} values obtained in the 35°C ambient temperature with no wind. The 60-min T_{re} with the utility uniform was 37.54°C compared with the 38.45°C found when the WW was added ($p<0.05$). The addition of the WC significantly reduced the 60-min T_{re} to 37.67°C. With the Mark III alone, 60-min T_{re} was 38.22°C; the WW gear over the Mark III increased the mean T_{re} response by 0.5°C ($p<0.05$). The addition of the WC effected a decrease in the 60-min T_{re} to 38.51°C, but this was not a significant reduction. The T_{re} values when the Norwegian suit was worn were similar (38.62°C) to those obtained with the Mark III + WW. When the Mark III and Norwegian suits were tested at 35°C with a 4.5 m/sec wind, T_{re} at 60 min was significantly reduced to 38.05°C and 38.37°C, respectively.

At 48.9°C (Figure 10), T_{re} of the subjects wearing the utility uniform was significantly higher than when tested at 22.2°C. Testing with the Mark III uniform produced a mean 60-min value of T_{re} of 38.70°C, which was significantly higher than the 60-min value of 38.22°C found in the 35°C environment.

The mean rates of rise of T_{re} for each of the environment-clothing combinations were calculated based on the total time each individual was able to remain in the heat and are presented in Table II. At 22.2°C, all clothing ensembles produced similar rates of rise of T_{re}. At 29.4°C, similar rises in core temperature were found with the utility, utility + WW, utility + WW + WC, Mark III and Mark III + WW + WC. The Mark III + WW and Norwegian suits, on the other hand, showed rises which were significantly higher than the other ensembles but which were similar to each other. In the 35°C environment, T_{re} rose at a similar rate for the utility uniform alone and for the utility + WW + WC. These rates of rise were no different from those observed at 22.2°

Table II. Rate of rise (mean ± S.E.) of rectal temperature (°C/h) for each clothing-environment combination

Ambient Temperature	22.2°	29.4°	35°	35° + Wind	48.9°
Clothing					
Utility	0.17 ± 0.05	0.21 ± 0.03	0.30 ± 0.04	-	0.39 ± 0.08
Utility + WW	0.21 ± 0.02	0.33 ± 0.03	1.23 ± 0.17	-	-
Utility + WW + WC	0.19 ± 0.04	0.21 ± 0.04	0.34 ± 0.04	-	-
Mark III	0.27 ± 0.05	0.32 ± 0.04	1.00 ± 0.07	0.51 ± 0.08	1.67 ± 0.10
Mark III + WW	0.39 ± 0.04	1.32 ± 0.13	1.86 ± 0.24	-	-
Mark III + WW + WC	0.25 ± 0.03	0.33 ± 0.05	1.28 ± 0.05	-	-
Norwegian	0.29 ± 0.04	1.00 ± 0.18	1.60 ± 0.08	1.35 ± 0.17	-

and 29.4°C. However, when the utility uniform was covered with the WW gear, T_{re} rose at a significantly faster rate than with the utility alone. Tests with the Mark III at 35°C demonstrated a rise in T_{re} which was more rapid than tests at 29.4°C ($p<0.05$). At 35°C, the Mark III also produced a greater rate of rise in T_{re} than that found with the utility control. Adding the WW gear over the Mark III further increased the rate of rise of T_{re} ($p<0.05$) to a level comparable with that observed for the Norwegian suit at 35°C. The addition of of the WC over the Mark III + WW produced a rate of rise which was similar to that of the Mark III alone. When the tests were conducted in a 4.5 m/sec wind at 35°C, the rate of rise of T_{re} was significantly reduced with both the Mark III and Norwegian compared to the 35°C tests with no wind. However, the difference in rates of rise between the Mark III and Norwegian suits still remained.

Mean Weighted Skin Temperature

The mean weighted skin temperatures ($\bar{T}_{sk}$) for each clothing-environment combination are presented in Figures 11-15. At all temperatures, the range of $\bar{T}_{sk}$ with the different clothing ensembles was quite dramatic. At 22.2°C (Figure 11), $\bar{T}_{sk}$ with the utility, utility + WW, utility + WW + WC, Mark III and Mark III + WW + WC followed identical response patterns in that the values continued to drop throughout the 3-hour exposure. The highest $\bar{T}_{sk}$ values were recorded with the Mark III + WW, followed by the Norwegian suit. No significant difference was evident between the Mark III and Mark III + WW + WC or between the utility and utility + WW + WC.

At 29.4°C (Figure 12), testing with the utility uniform alone and with the utility + WW + WC produced final $\bar{T}_{sk}$ values which were at least 1.5°C less than any other ensemble. The 90-min $\bar{T}_{sk}$ values for the Mark III, Mark III + WW + WC and utility + WW were similar at ∿35.2°C. $\bar{T}_{sk}$ rose very rapidly with the Mark III + WW and the Norwegian, so that after 90 minutes, the values recorded were 37.2° and 36.6°C, respectively, and were significantly higher than the values obtained for the other ensembles.

Figure 13 shows the $\bar{T}_{sk}$ values at 35°C. Final $\bar{T}_{sk}$ was significantly higher for all ensembles at this temperature. While the utility and utility + WW + WC showed similar values at 22.2° and 29.4°C, the difference between these two ensembles widened by 0.5 to 1.0°C over the duration of the test. Final (60 min) $\bar{T}_{sk}$ values for all other ensembles were >37.0°C, with the Mark III + WW demonstrating the highest value at 38.6°C. This was significantly greater than that observed with the Norwegian uniform (37.9°C). Final values for the utility + WW, Mark III + WW + WC and Mark III were all similar at ∿37.2°C.

Figure 14 demonstrates the effect a 4.5 m/sec wind had on the $\bar{T}_{sk}$ response at 35°C, 60% r.h. When tested with the Mark III and no wind, "final" $\bar{T}_{sk}$ at 60 min was 37.0°C. This was significantly lowered with the 4.5 m/sec wind to 36.0°C, for a reduction of 1.0°C. At 60 min, the final $\bar{T}_{sk}$ for the Norwegian suit was 37.9°C with no wind and 37.4°C with the 4.5 m/sec wind, for a change of 0.5°C.

At 48.9°C (Figure 15), final $\bar{T}_{sk}$ with the utility uniform was 35.9°C, which was significantly higher than the value observed at 35°C. For the Mark III uniform, final $\bar{T}_{sk}$ at 50 min was 37.4°C, a value significantly greater than that observed with the utility uniform.

Rectal-to-Mean Skin Temperature Gradient

Table III presents a summary of the final T_{re} - $\bar{T}_{sk}$ gradients for each environment-clothing combination. The lowest gradient at 22.2°, 29.4°, and 35°C was observed with the Mark III + WW followed by the Norwegian suit. The largest gradients were found with the utility and utility + WW + WC ensembles. The 4.5 m/sec wind served to significantly increase the T_{re}-$\bar{T}_{sk}$ gradient for both the Mark III and the Norwegian uniforms. With no wind, the mean gradients were 1.95° and 0.70°C for the Mark III and Norwegian suits, respectively. The addition of the 4.5 m/sec wind increased these gradients by 0.4°C and 0.8°C, respectively.

Sweat and Evaporation Rates

Mean ($\pm$ S.E) values for the sweat (SR) and evaporation rates (EVAP) measured for each clothing-environment combination are presented in Figures 16 through 19. From these graphs, several points become quite obvious. First, although the WW gear over the uniforms should have made the entire ensemble impermeable, evaporation of sweat was measured. These losses could have resulted from evaporation through the mask and/or from the head during rest periods when some individuals pulled the mask off to drink water. The second obvious point from the figures is the very high rate of evaporation noted from the wettable cover tests. As described in the METHODS section, the procedure utilized for measuring evaporation from the wettable cover involved wetting the individual down and then reweighing him. Although precautions were taken to reduce dripping of water, it is apparent that some dripping did occur and was subsequently measured as evaporated water.

For all environments, the SR's measured with the WC were significantly lower than those values observed with the WW gear alone. On the other hand, EVAP's were significantly greater for tests conducted with the WW + WC. All clothing ensembles except the utility and utility + WW + WC had significantly higher SR's at 29.4° than at 22.2°C (Figures 16 & 17). Because of the large inter-individual variation, no significant differences in EVAP among the clothing systems were observed at 22.2° and 29.4°C. All tests at 35°C (Figure 18) elicited significantly higher SR's than those observed at 29.4°C. Although EVAP's tended to be higher at 35°C for all ensembles, the values were not significantly different from those at 29.4°C. The addition of the wind at 35°C significantly decreased the rate of sweat production while increasing the rate of evaporation for both the Mark III and the Norwegian uniforms. Evaporation rates with the 4.5 m/sec wind were greater for the Mark III than for the Norwegian suits. At 48.9°C (Figure 19), SR and EVAP's were significantly increased from those values observed at 35°C.

The highest SR's observed in all the environments were for the Mark III + WW and the Norwegian uniforms, followed by the Mark III, Mark III + WW + WC, and utility + WW ensembles. As mentioned above, the highest measured EVAP's were found for the ensembles tested with the wettable covers. At 22.2°, 29.4°, and 35°C, EVAP's for the remaining five ensembles showed no differences among each other, except for the lowered rates noted when the WW gear was worn.

Table III. **Final rectal-to-skin temperature gradients (mean ± S.E.) for each clothing-environment combination**

Ambient Temperature(°C)	22.2°	29.4°	35°	35° + Wind	48.9°
Clothing					
Utility	6.00 ± 0.33	4.54 ± 0.23	2.67 ± 0.37	-	2.12 ± 0.39
Utility + WW	4.87 ± 0.26	2.76 ± 0.07	1.57 ± 0.23	-	-
Utility + WW + WC	6.12 ± 0.36	5.11 ± 0.26	2.54 ± 0.16	-	-
Mark III	4.19 ± 0.26	3.35 ± 0.23	1.95 ± 0.20	2.39 ± 0.30	1.44 ± 0.18
Mark III + WW	2.76 ± 0.20	1.59 ± 0.09	0.31 ± 0.10	-	-
Mark III + WW + WC	4.43 ± 0.25	3.11 ± 0.33	1.80 ± 0.09	-	-
Norwegian	3.76 ± 0.22	2.25 ± 0.27	0.70 ± 0.09	1.50 ± 0.10	-

Subjective Comments

Generally, all uniforms were easy to don, and the overall fit of the six different ensembles was described as "good." However, half of the subjects felt that the Norwegian suit was stiff and not very comfortable. In the warm climates (>29.4°C), the Norwegian and Mark III + WW were described as "hot" by all participants, while the Mark III alone was thought to be "comfortable" by 5 of the 8 volunteers. When the Mark III + WW + WC was worn, body movement was impaired in the crotch, neck, underarms, and legs, with the neck and underarms being the most frequent areas of impairment.

By far, the most complaints involving the clothing centered on the Mark V mask. All subjects described the mask as extremely uncomfortable, while 5 of the 8 reported that the mask consistently impaired their vision because of fogging of the lens. In several of the subjects, the headstraps produced pressure headaches. Finally, 6 of the 8 individuals complained of an ammonia smell through the cannisters after the mask had been worn for long periods of time.

DISCUSSION

Throughout these evaluations, a gradation in responses to the clothing-environment combinations was evident. The uniforms evoking the least physiological strain were the utility and the utility + WW + WC, followed by the Mark III, the utility + WW, and the Mark III + WW + WC. The least acceptable ensembles were the Mark III + WW and the Norwegian suits. Based on tolerance times, tests with the Mark III showed that, under a moderate heat stress (WBGT = 23.6°C), a person could work only 50 and 75% as long with the Mark III + WW and the Norwegian uniforms, respectively, than with the Mark III alone. In a more stressful environment (WBGT = 30.3°C), all protective garments reduced tolerance time compared with the control by at least 31% (Mark III) and up to 75% (Mark III + WW), with the Norwegian suit demonstrating a 66% reduction in tolerance time. These times were shown to be somewhat increased with the addition of a 4.5 m/sec wind. Thus, individuals testing with the Norwegian uniform at 35°C with wind showed only a 50% reduction in tolerance time compared with the 66% with no wind; and those tested with the Mark III in the wind improved their tolerance to 87% of that observed with no protective clothing.

It was also shown that the addition of a wettable cover over an impermeable garment can significantly improve tolerance time in the heat. When the Mark III + WW + WC was tested under the moderate heat stress, tolerance time returned to the value observed with the Mark III alone (180 min). At 35°C, the addition of the WW to the utility uniform decreased tolerance time by 40%; however, the WC reduced this decrease to only 13%. When the WW was added to the Mark III, tolerance time decreased by 64% compared with the Mark III alone. The wettable cover added to the ensemble diminished this reduction to 31%.

Based on the rate of heat storage (calculated as $S = \Delta\bar{T}_b \cdot 0.97 \cdot wt$, where $\Delta\bar{T}_b$ = change in mean body temperature, 0.97 = specific heat of the body in W·h/kg/°C and wt = body wt in kg), the time to 50% heat casualties can be predicted (2). If it is assumed that the "safe" limit for total heat storage is 185 W·h, dividing this number by the calculated rate of heat storage (in W) would give the time required to reach this heat storage limit. At 22.2°C, tolerance times for all clothing were >8 hours since the heat storage was minimal. At 29.4°C, the time to 50% casualties for the Mark III + WW was 1.84 ± 0.2 h; this time was increased to 12.5 ± 3.8 h when the WC was added to this ensemble. With the Norwegian suit, time to 50% casualties was 2.9 ± 0.9 h. All other ensembles had predicted tolerance time >8 h. At 35°C, tolerance time was still predicted to be >8 h for the utility alone and the utility + WW + WC. However, with the WW over the utility, predicted tolerance time was reduced to 2.4 ± 0.6 h. With the Mark III alone, maximal permissible heat storage would be expected to occur at 2.7 ± 0.3 h, compared with 1.2 ± 0.1 h and 2.1 ± 0.2 h with the WW gear and the WW + WC, respectively, over the uniform. Time to 50% heat casualties is predicted to occur at 1.4 ± 0.1 h with the Norwegian suit worn in a 35°C, 60% r.h. environment. Predicted tolerance time increased to 6.4 and 2.0 h for the Mark III and the Norwegian suits, respectively, with the addition of a 4.5 m/sec wind. At 48.9°C, it would be expected that an individual wearing the utility uniform can work at the rate tested in this series of experiments (170 W/m^2) for >8 h. With the Mark III, however, tolerance time would be limited to 1.5 ± 0.1 h.

The obvious reason for the low tolerance while working in the Norwegian and Mark III + WW ensembles is the impermeability of the garments. In a totally impermeable ensemble, the maximum evaporative capacity of the environment (E_{max}) would approach 0 W. When $\bar{T}_{sk}$ is greater than ambient temperature, such as in the 22.2° and 29.4°C environments, the minimal E_{max} could be somewhat compensated by the dry heat losses via radiation and convection (R+C). Tolerance time would thus be limited by a combination of the temperature differential between the skin and the air and the metabolic heat production. At 35°C, however, the temperature gradient between the skin and the air is minimal; therefore, all heat loss must occur via evaporation of sweat through the garments. Since evaporation is hindered in impermeable clothing, skin temperature will rise more rapidly than T_{re}, thus diminishing the $T_{re} - \bar{T}_{sk}$ gradient (see Table III) required for heat transfer to the periphery. As rectal and skin temperatures converge, cardiovascular collapse will be imminent since such large quantities of blood have been shunted from the central core area to the periphery in an attempt to dissipate body heat.

The ratio EVAP/SR, or the proportion of sweat which evaporates from the skin, may be regarded as the efficiency of sweating. These ratios were calculated from the measured sweat and evaporation rates and are presented in Table IV. As is evident, the efficiency of sweating was drastically reduced in those ensembles which could be considered to be impermeable. (The values for the utility + WW at 22.2° and 29.4°C may have been inflated because of the small numbers which were measured for sweat and evaporation.) The EVAP/SR ratio diminished for all ensembles with the higher humidity environments. In the 35°C environment, only 9% of the sweat produced with the Mark III + WW was evaporated. For tests conducted in the 4.5 m/sec wind, the efficiency of sweating was found to increase. Thus, while only 29% of the sweat evaporated in no wind at 35°C with the Mark III uniform, 49% was evaporated when testing was conducted with wind. Similarly, when the 4.5 m/sec wind was added,the Norwegian suit demonstrated an increase in the sweating efficiency compared with the no wind test.

The Norwegian suit was designed as a partially-permeable garment (see Appendix A). The outer layer is impermeable to water, but filtered openings, or ventilation flaps, totaling approximately one-third of the surface area of the suit, have been provided to allow penetration of air but not toxic gases. The rationale behind this design was to allow "bellows ventilation" (8) to take place while the body is in motion. Additionally, wind blowing onto this garment should substantially increase the rate of evaporation from the skin surface. When the Norwegian suit was compared with a totally impermeable Canadian CW overgarment in an 18°C, 40-60% r.h. environment with wind speed of 0.25 m/sec (9), it was found that similar changes in body heat content were measured in both uniforms. The amount of sweat evaporated was significantly higher in the Norwegian suit than in the impermeable garment, with 16% of the produced sweat evaporated. In the series of tests reported here, the Norwegian suit demonstrated sweating efficiencies of 40, 35, and 21% in the 22.2°, 29.4°, and 35°C environments, respectively. Our values for efficiency of sweating are somewhat higher than those reported by Rodahl et al (9). However, our minimal wind velocity was four times that of their study; hence, the rate of sweat

8. Vokac, Z., V. Kopke, and P. Keul. Assessment and analysis of the bellows ventilation of clothing. Textile Research Journal 43:474, 1973.
9. Rodahl, F., T. Wessel-Aas, P.O. Huser, and T. S. Nilsen. A physiological evaluation of a waterproof, partially permeable protective suit against chemical and bacteriological warfare. In preparation.

Table IV. Efficiency of sweating (evaporation-to-sweat rate ratio) for all environment-clothing combinations except those in which the WC was added to the ensembles (see text)

Ambient Temperature	22.2°C	29.4°C	35°C	35°C + Wind	48.9°C
Clothing					
Utility	0.91	0.84	0.71	-	0.86
Utility + WW	0.49	0.54	0.34	-	-
Utility + WW + WC	-	-	-	-	-
Mark III	0.60	0.50	0.29	0.49	0.36
Mark III + WW	0.27	0.16	0.09	-	-
Mark III + WW + WC	-	-	-	-	-
Norwegian	0.40	0.35	0.21	0.30	-

evaporation would be expected to be higher for our testing conditions. In a comparison between our impermeable garment (Mark III + WW) and the Norwegian suit, we similarly found that thermal parameters, such as HR and T_{re}, were equal in the two garments. The only significant differences between the Mark III + WW and the Norwegian ensembles were found in the $\bar{T}_{sk}$ values at 29.4° and 35°C, in which the Norwegian tests elicited lower $\bar{T}_{sk}$ values than did the Mark III + WW. Although not significant, EVAP's were higher with the Norwegian suit compared with the Mark III + WW at 29.4° and 35°C.

The WC was used in this series of experiments in an attempt to increase the evaporation from the surface of an impermeable garment, thereby cooling the outer layer and permitting sensible and evaporative heat losses from the skin surface. Breckenridge (6) has validated, on a heated copper manikin, a mathematical model, which was based on physical relationships for heat exchange between clothed man and his environment, describing the cooling effect of a wettable cover over an impermeable garment. In a 1.0 m/sec wind at 25°C/50% r.h., an additional 67 W of cooling would be expected with a WC. In 30°C/40% r.h., supplementary cooling would be 83 W; and at 35°C/60% r.h., 58 W of added cooling to the individual would be expected. For the physiological trials conducted with the WC, the additional cooling benefit of the WC could be determined by calculating the difference between the rates of heat storage with and without the WC over the WW gear, as seen in Table V. Under the conditions of our tests, addition of the WC to the utility uniform provided supplemental cooling benefits ranging from 5 to 78 W, depending upon environment. With the Mark III, the WC was responsible for additional evaporative cooling rates of 15, 85 and, 70 W in the 22.2°, 29.4°, and 35°C tests, respectively. The less stressful environment (22.2°C) showed less supplemental cooling than predicted for both the utility and the Mark III ensembles. At 29.4°C, the Mark III ensemble appeared to fit the model quite well, while at 35°C, both the utility and Mark III ensembles showed supplemental cooling effects somewhat higher than those predicted.

When making comparisons with the predicted values (6), it should be borne in mind that the two studies did not use identical clothing ensembles. In our study, there was no exposure with the WW + WC with WC dry, while the prediction values were based on a comparison between the WC wet and dry. Hence, some differences in relative insulation between our measured, and Breckenridge's predicted, supplemental cooling benefits should be expected.

Table V. Rates of heat storage (in W) for wet weather (WW) and wettable cover (WC) ensembles

Ambient Temperature	Utility +WW	Utility +WC	Difference
22.2°C	8	3	5
29.4°C	24	12	12
35.0°C	98	20	78
	Mark III +WW	Mark III +WC	Difference
22.2°C	30	15	15
29.4°C	106	21	85
35.0°C	163	92	70

CONCLUSIONS

1. The Mark III permeable CW uniform elicits the least physiological strain when worn by individuals working in hot environments. However, tolerance time is still diminished compared with the control condition (utility uniform), with decreases of 31 and 63% in warm humid and hot dry environments, respectively.

2. The impermeable uniforms (Mark III + WW and Norwegian) create intense thermal stress, such that tolerance time is reduced by more than half in a warm humid climate with moderate work.

3. A WC over an impermeable uniform can significantly increase tolerance time in the heat by increasing evaporative and sensible heat loss through the layers of clothing.

Acknowledgements

This author wishes to express sincere appreciation to Mr. Jim Shampine, Mr. Joe Giblo, Mr. Bob Keene, and Ms. Fernanda Demorais for their assistance in the collection, reduction, and analysis of the data. A special thanks is also extended to Miss Margaret Spinazola for her patience in typing the manuscript.

APPENDIX A

Description of Chemical-Protective Clothing

British Mark III

The two-piece British Mark III uniform (Figure 20) is a lightweight (1.3 kg) CBR suit which offers the wearer 24-hour protection in a toxic environment. The chemically protective inner material on this uniform is a flame-retardant, air-permeable, reinforced nonwoven fabric, treated with fluorocarbon liquid repellent to resist entrance of toxic liquids. The fabric also contains a firmly anchored layer of activated charcoal to provide toxic gas and vapor protection. The outer material of this uniform is made of modacrylic fibers with polyamide reinforcement for strength and durability. This fabric is given a light silicone treatment to showerproof standards, but allows organic liquids to spread rapidly, aiding evaporation and eliminating overloading of the charcoal protective inner layer.

Norwegian Helly Hansen (NM 77)

The Norwegian suit (Figure 21) is described as a semi-permeable chemical protective garment. The outer material, which is resistant to penetration by liquid chemical agents, is composed of a polyamide fabric coated with butyl rubber laminated to an interlining and a polyvinylfluoride film. The suit has large ventilated areas in the front and back, in the crotch, and in the back of the head. These ventilated areas are covered by filters made of nonwoven fabric or polyurethane foam coated with activated carbon. The filter pieces may be exchanged and are fixed to the outer material by Velcro. All filters are covered by impermeable material, which will protect the filters against liquids and prevent excessive airflow through the filters. The purpose of the filters is to provide airflow, and hence evaporative cooling, through the garment. Wind velocity and the pumping effect of the wearer's movements should act to increase the rate of sweat evaporation through an otherwise impermeable uniform.

APPENDIX B. ILLUSTRATIONS

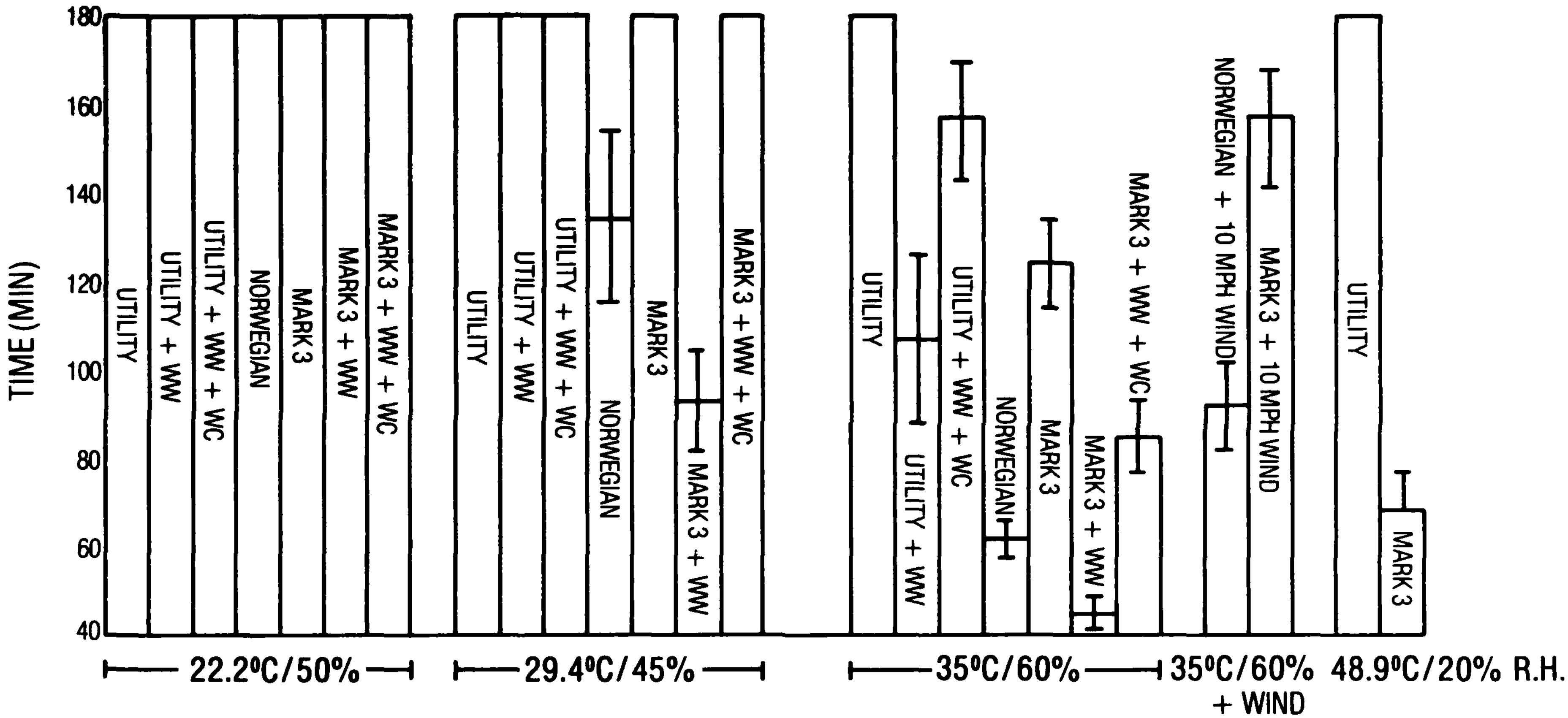

Figure 1. Tolerance times for each clothing-environment combination.

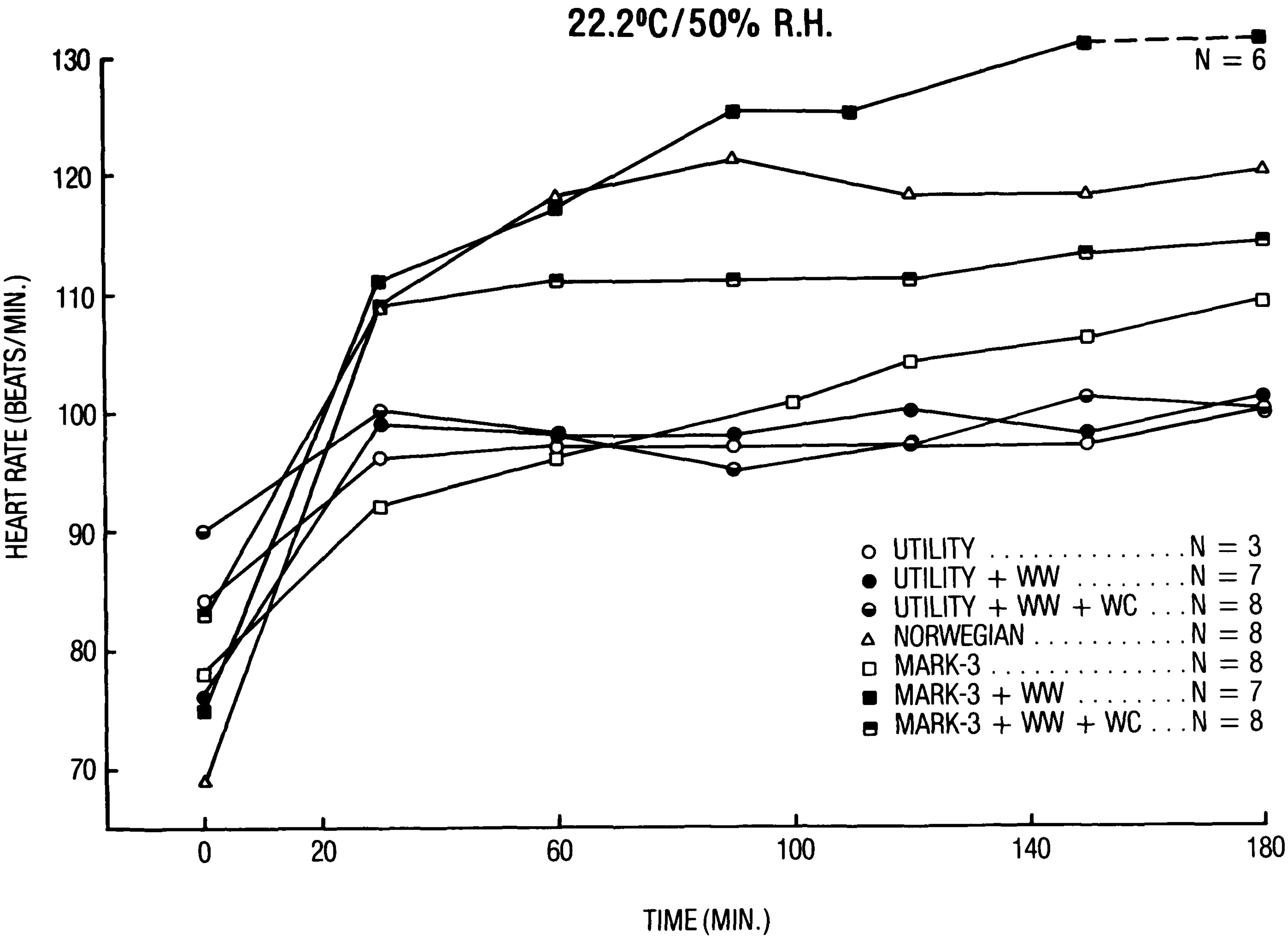

Figure 2. Half-hourly heart rate values for each clothing ensemble tested at 22.2°C.

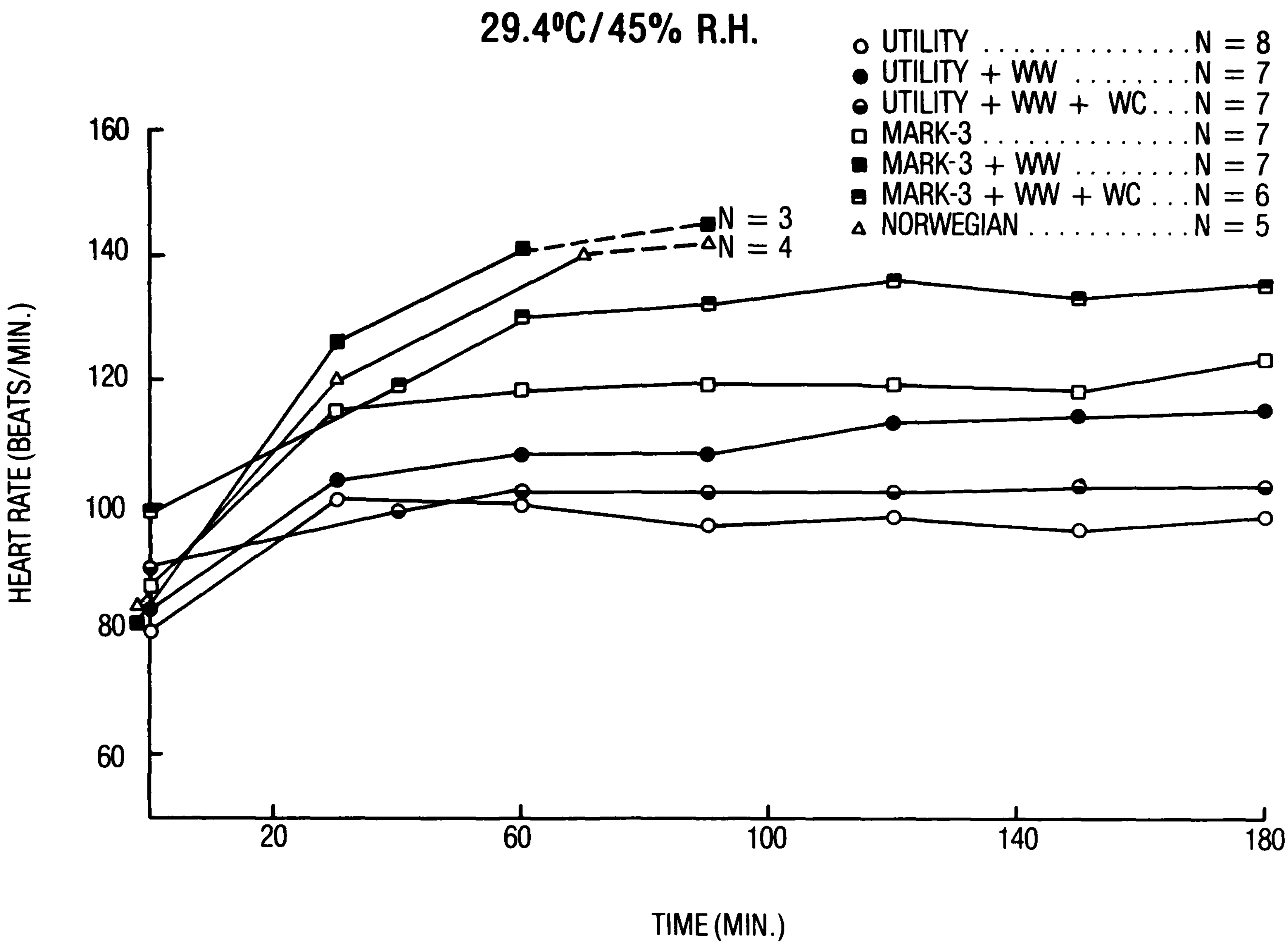

Figure 3. Half-hourly heart rate values for each clothing ensemble tested at 29.4°C.

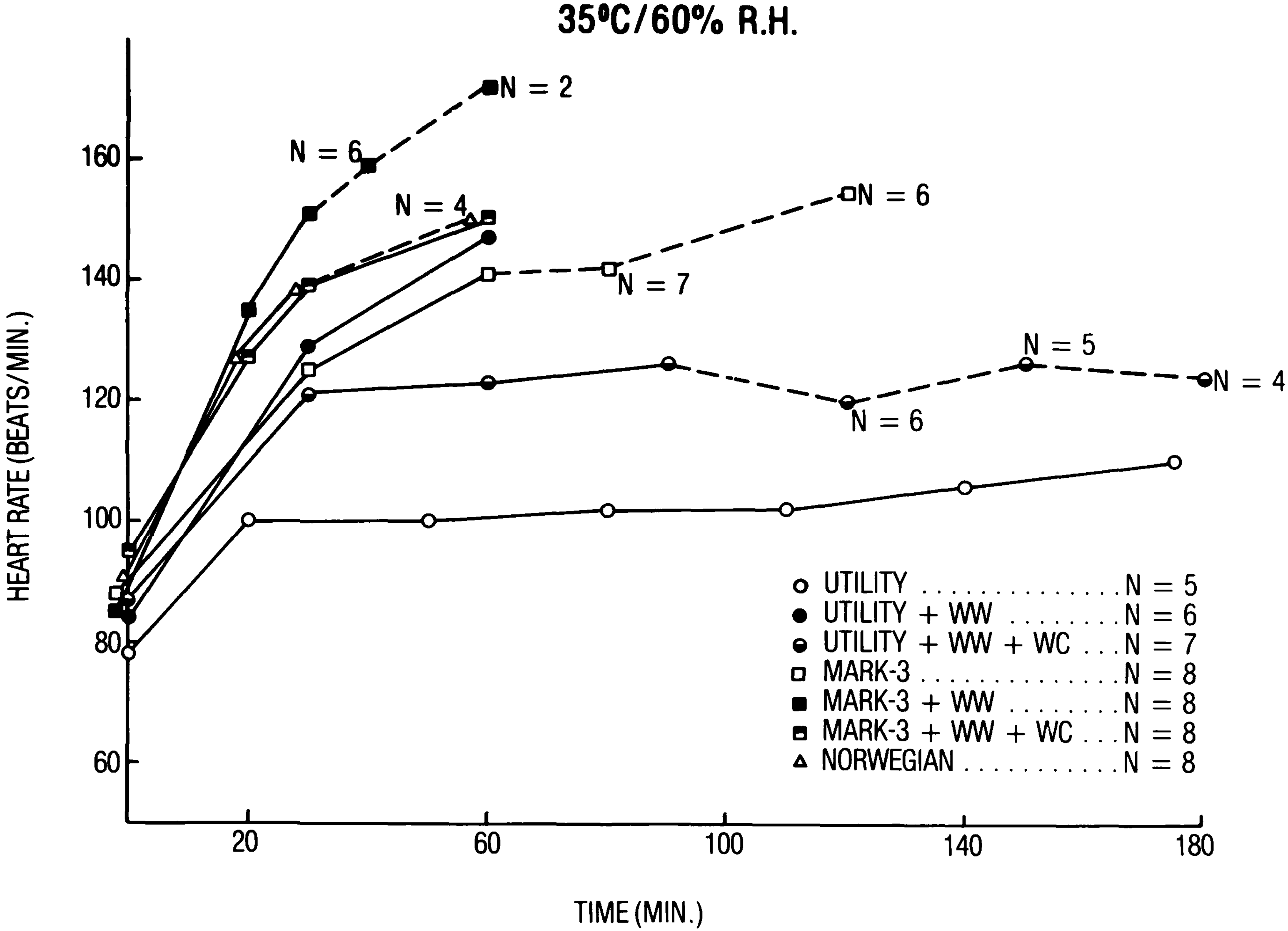

Figure 4. Half-hourly heart rate values for each clothing ensemble tested at 35°C, without wind.

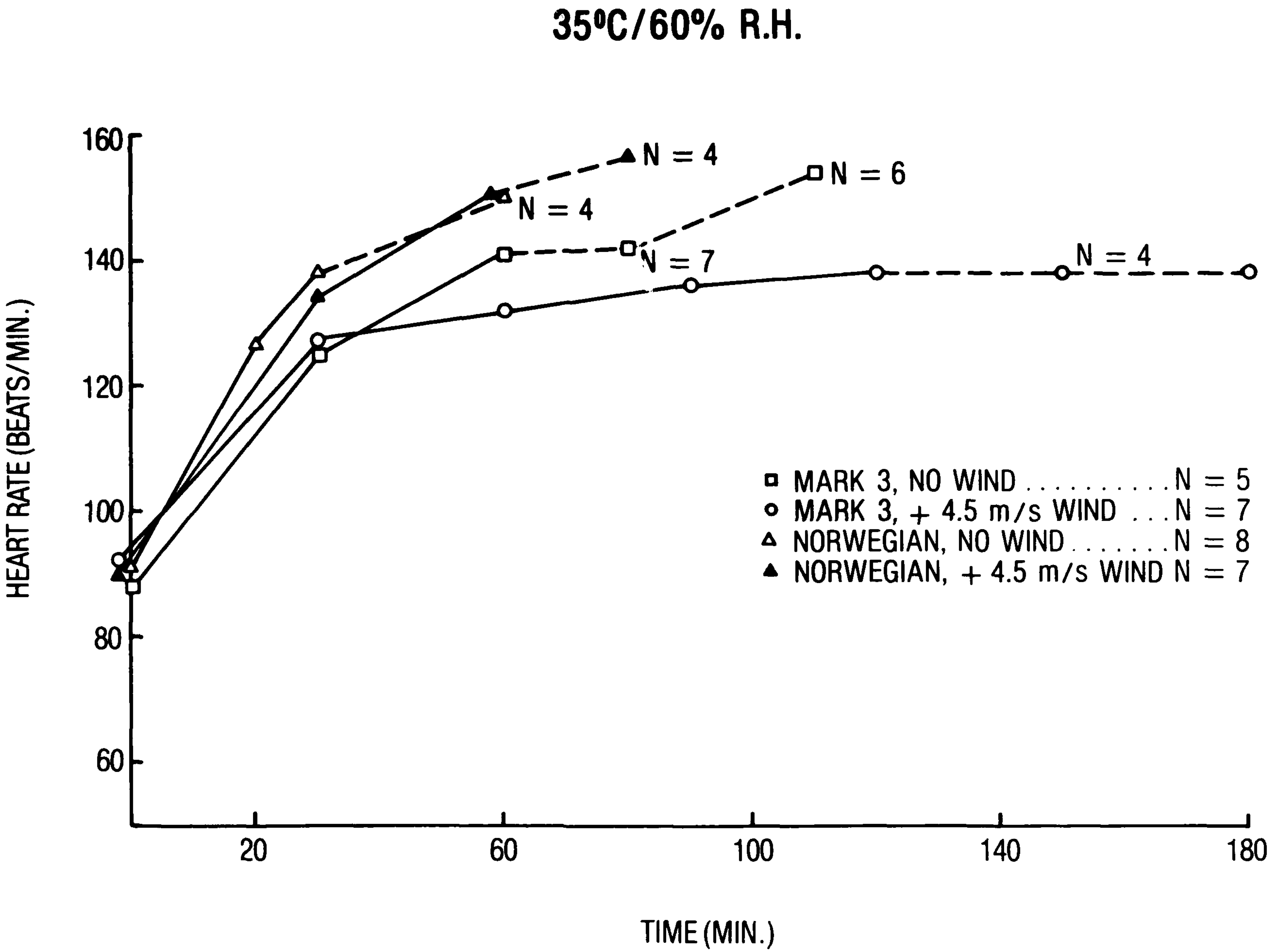

Figure 5. Half-hourly heart rate values for each clothing ensemble tested at 35°C, without and with wind.

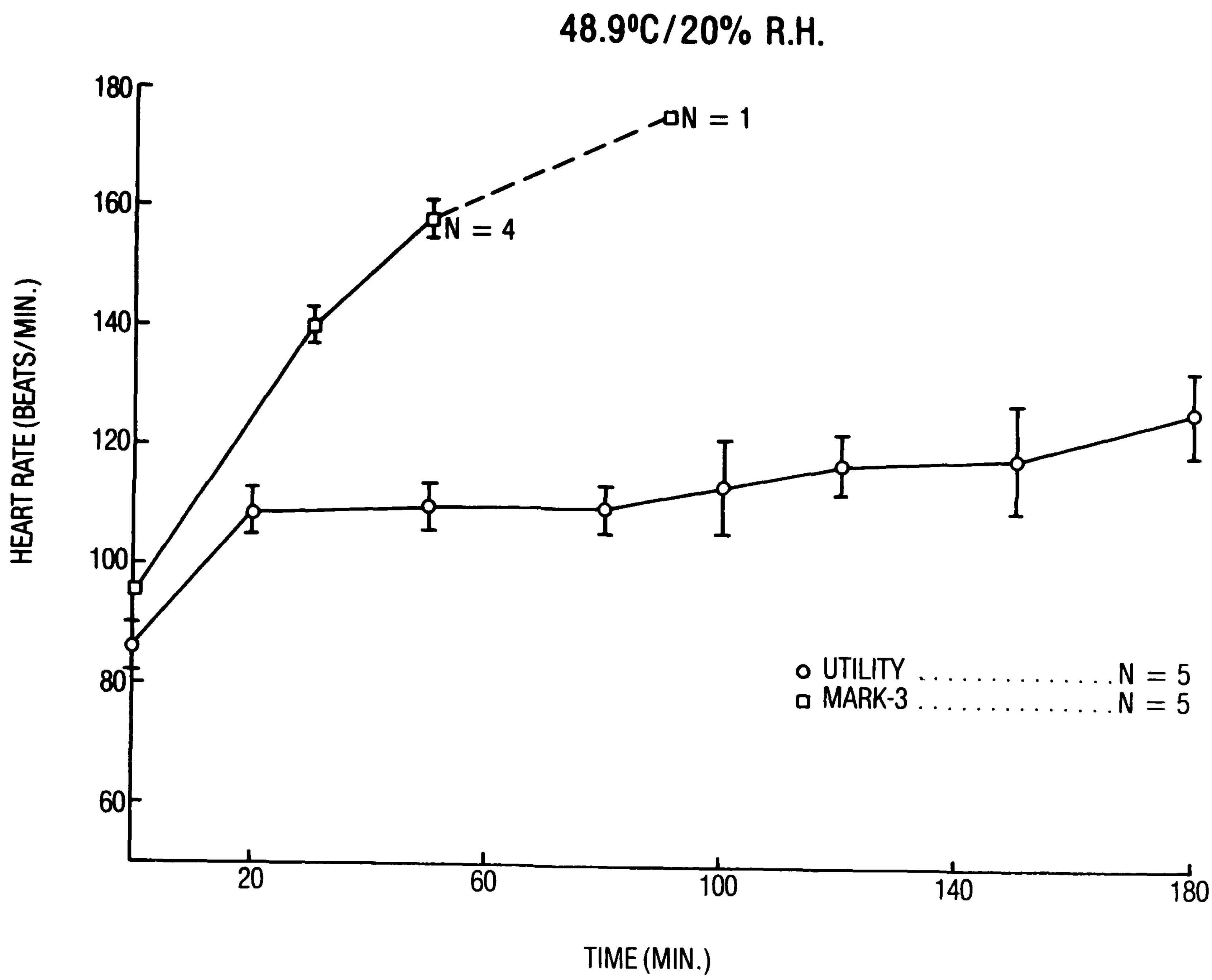

Figure 6. Half-hourly heart rate values for each clothing ensemble tested at 48.9°C.

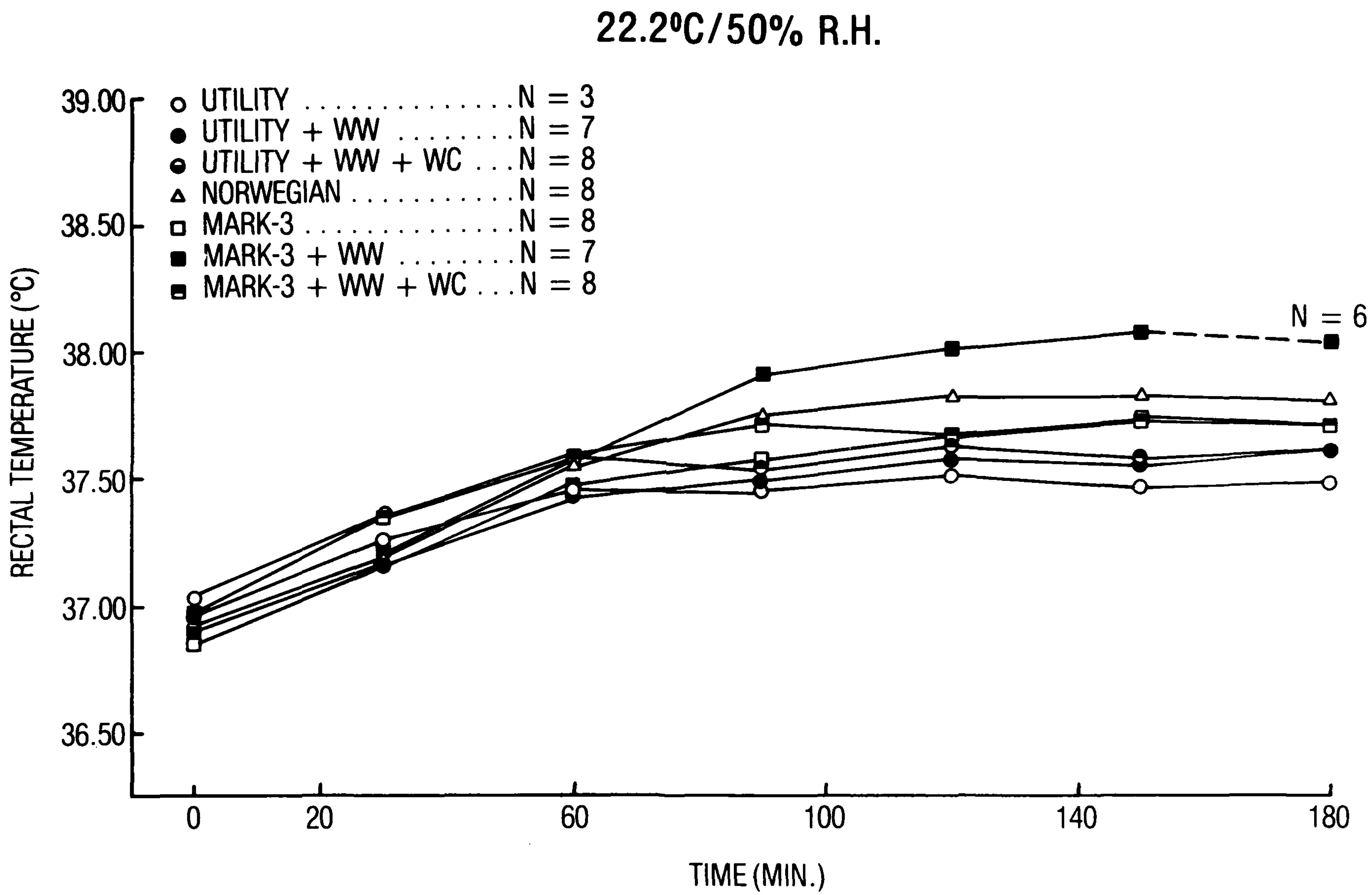

Figure 7. Half-hourly rectal temperature values for each clothing ensemble tested at 22.2°C.

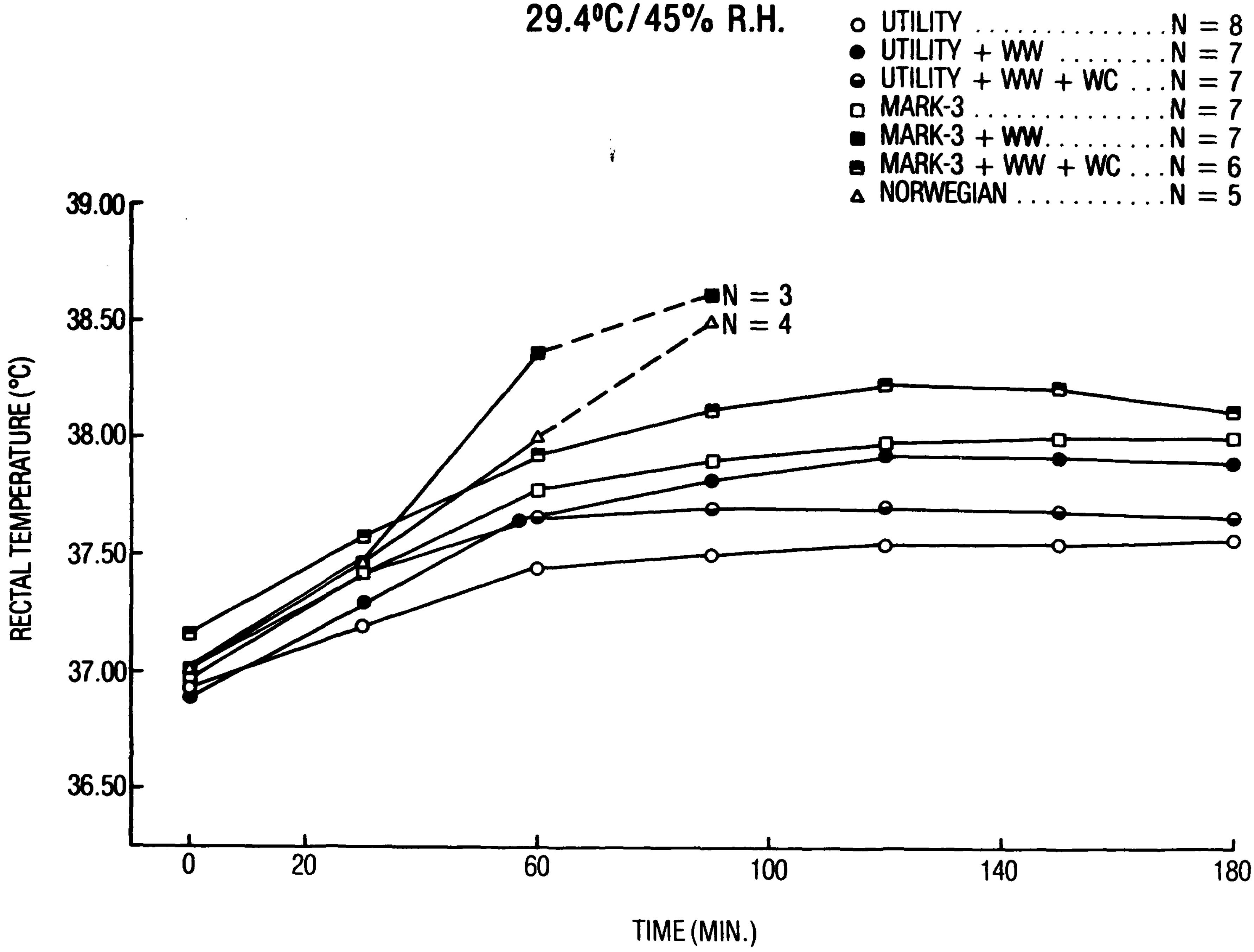

Figure 8. Half-hourly rectal temperature values for each clothing ensemble tested at 29.4°C.

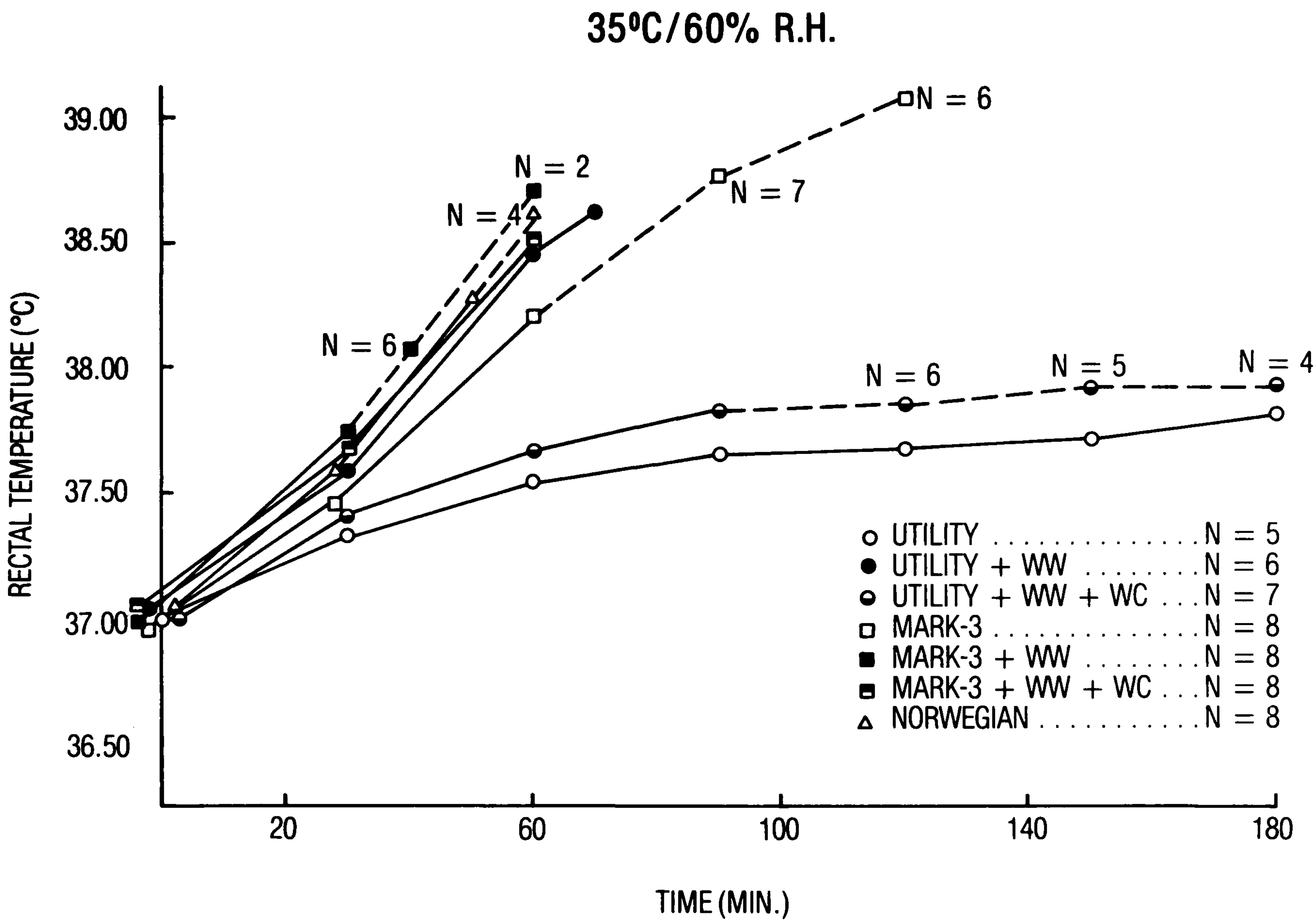

Figure 9. Half-hourly rectal temperature values for each clothing ensemble tested at 35°C, without wind.

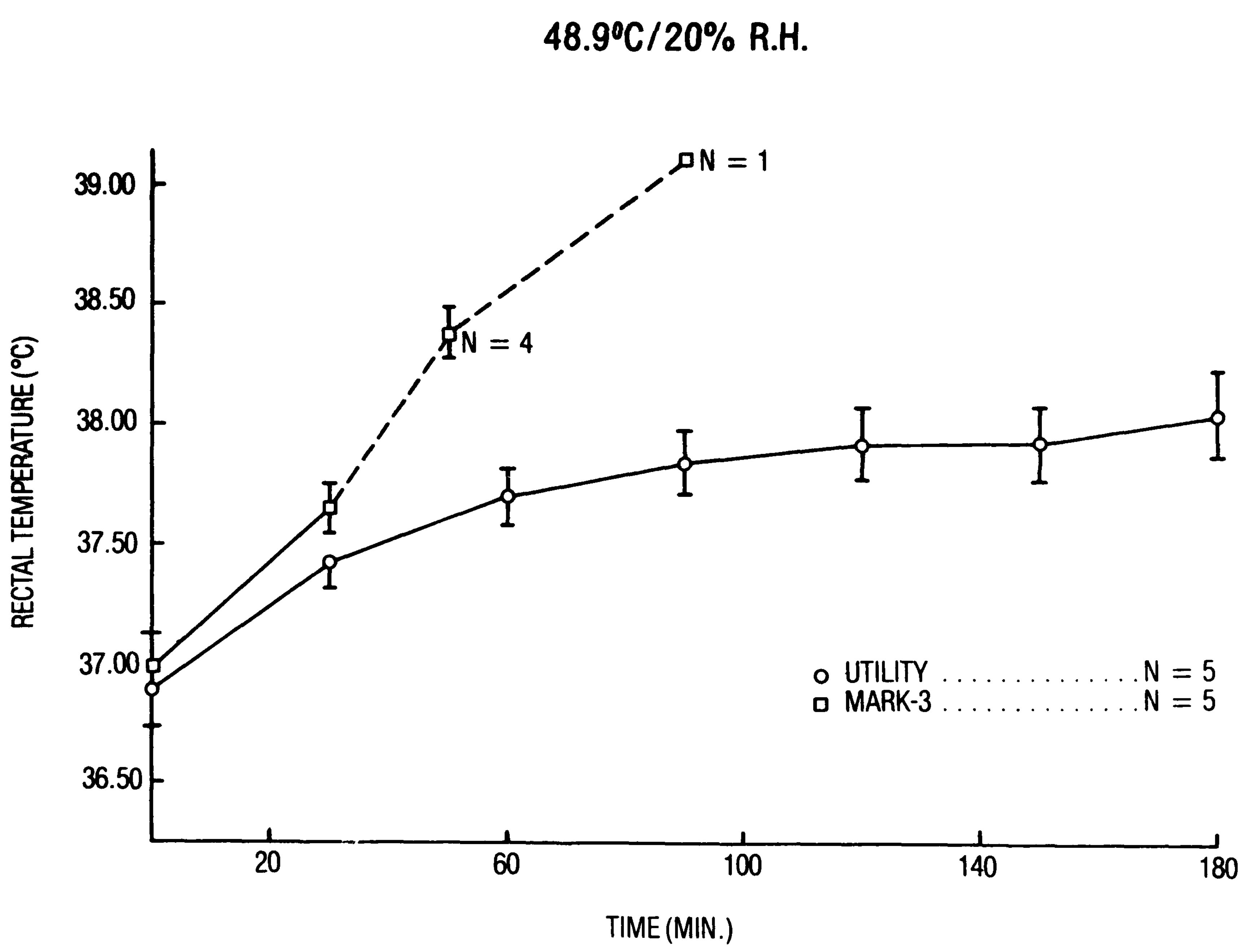

Figure 10. Half-hourly rectal temperature values for each clothing ensemble tested at 48.9°C.

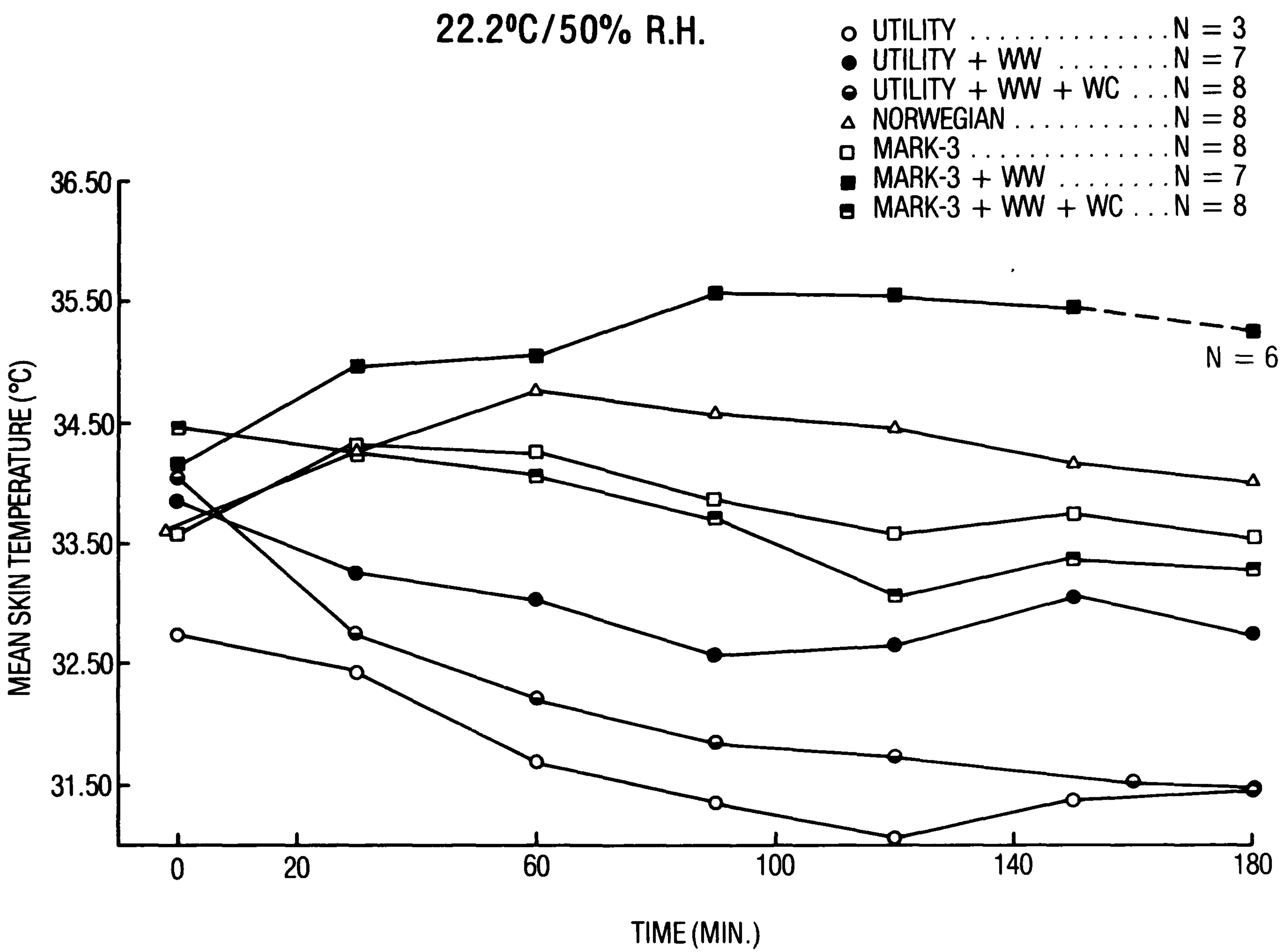

Figure 11. Half-hourly mean skin temperature values for each clothing ensemble tested at 22.2°C.

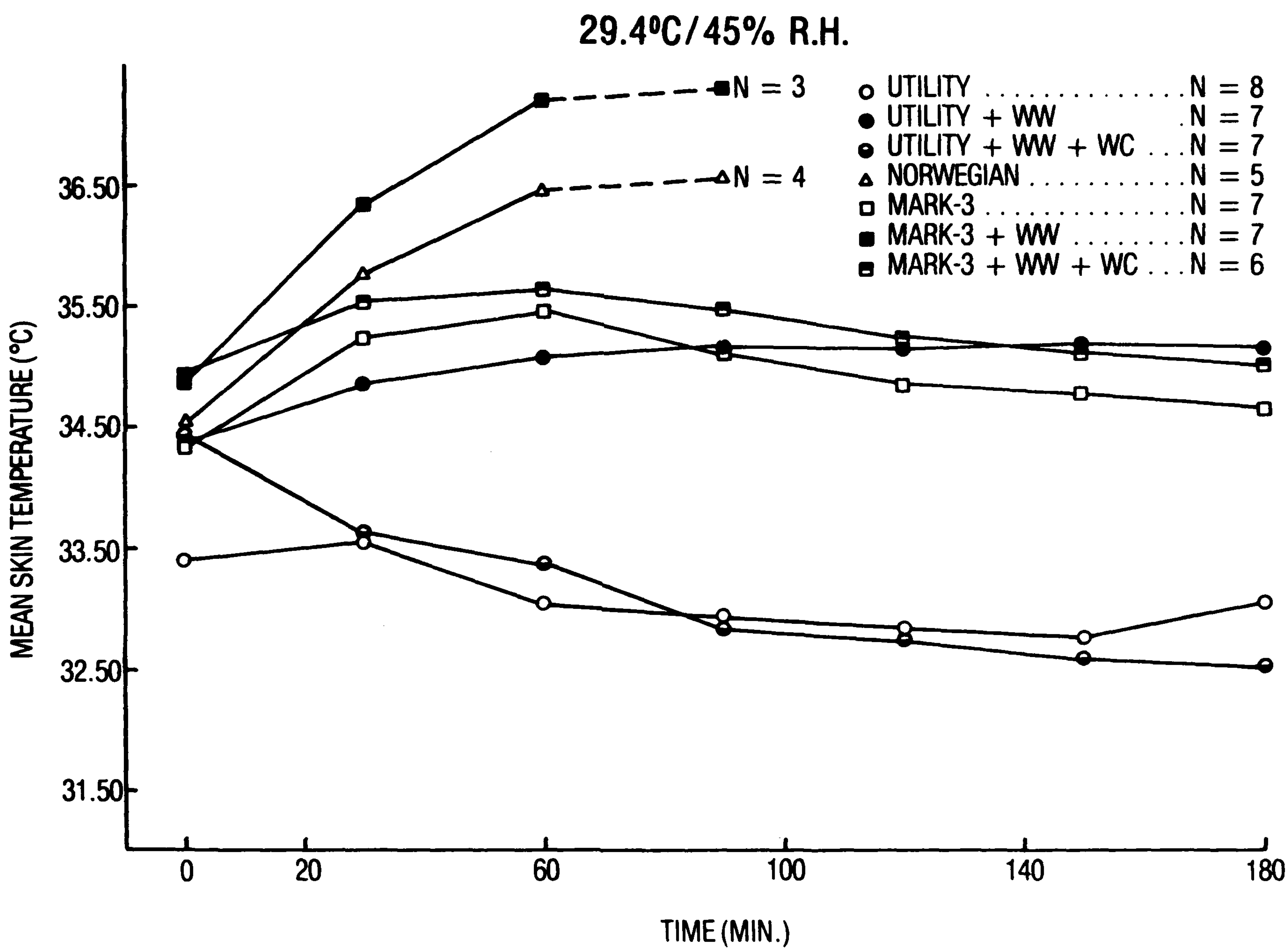

Figure 12. Half-hourly mean skin temperature values for each clothing ensemble tested at 29.4°C.

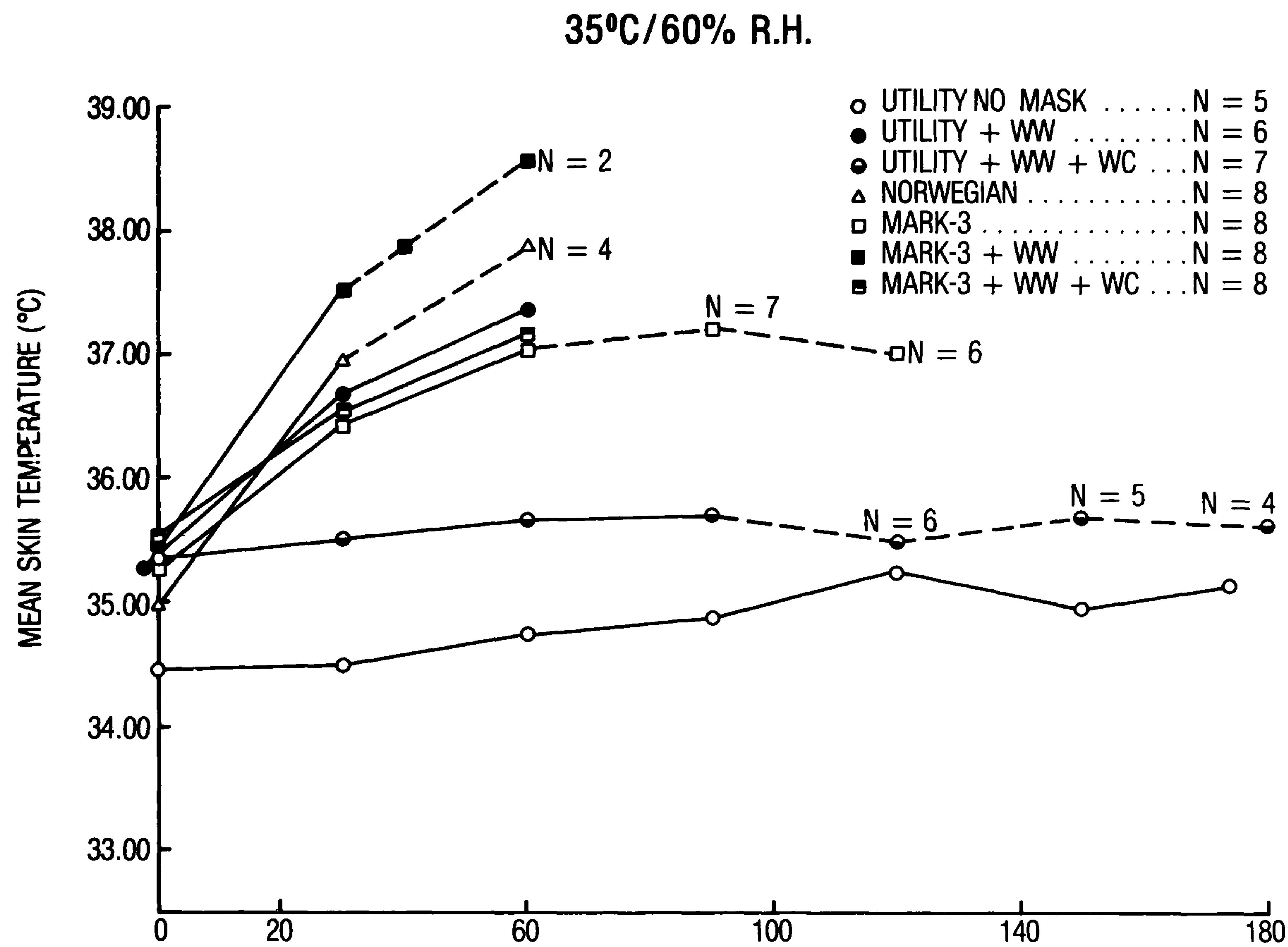

Figure 13. Half-hourly mean skin temperature values for each clothing ensemble tested at 35°C, without wind.

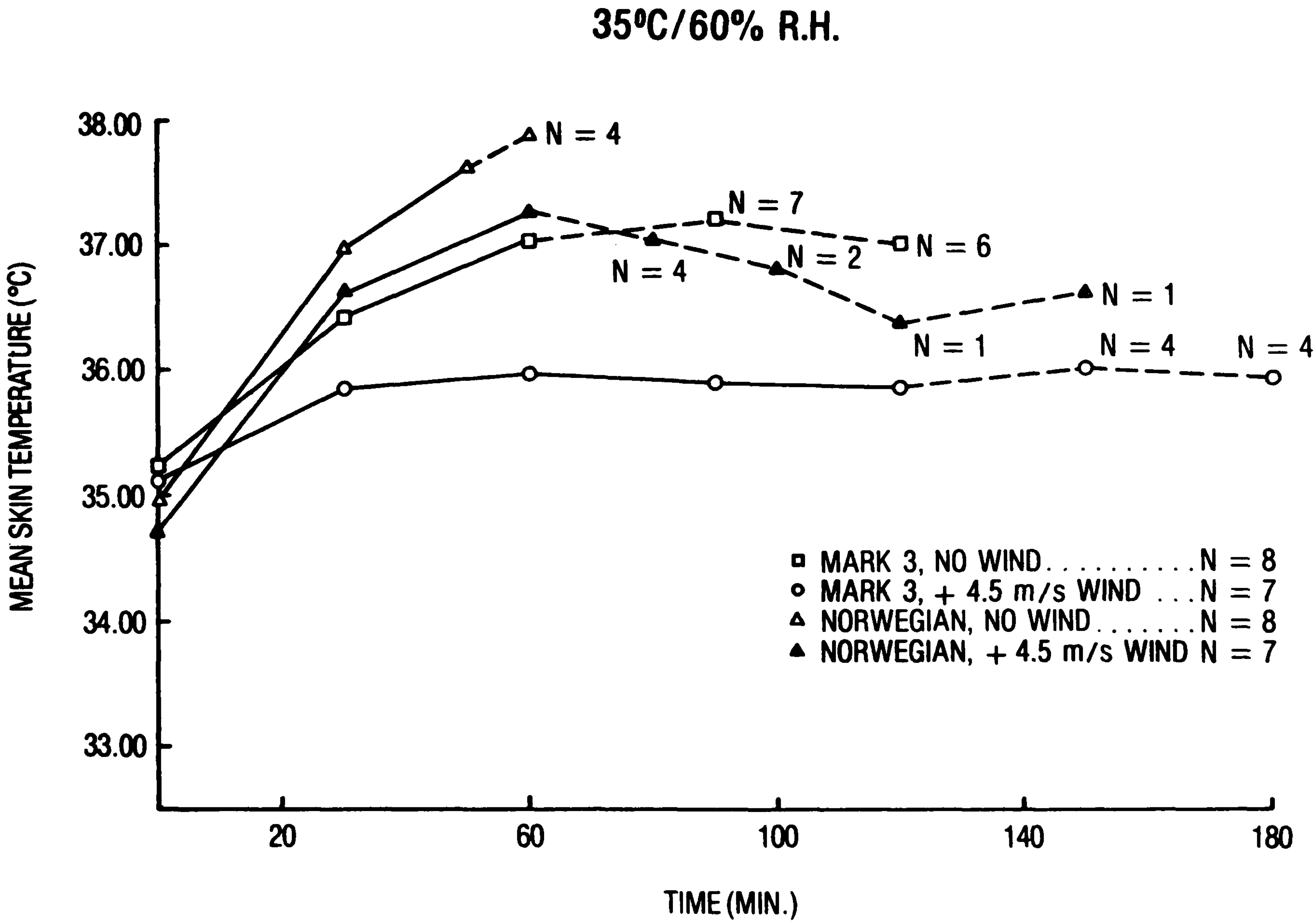

Figure 14. Half-hourly mean skin temperature values for each clothing ensemble tested at 35°C, without and with wind.

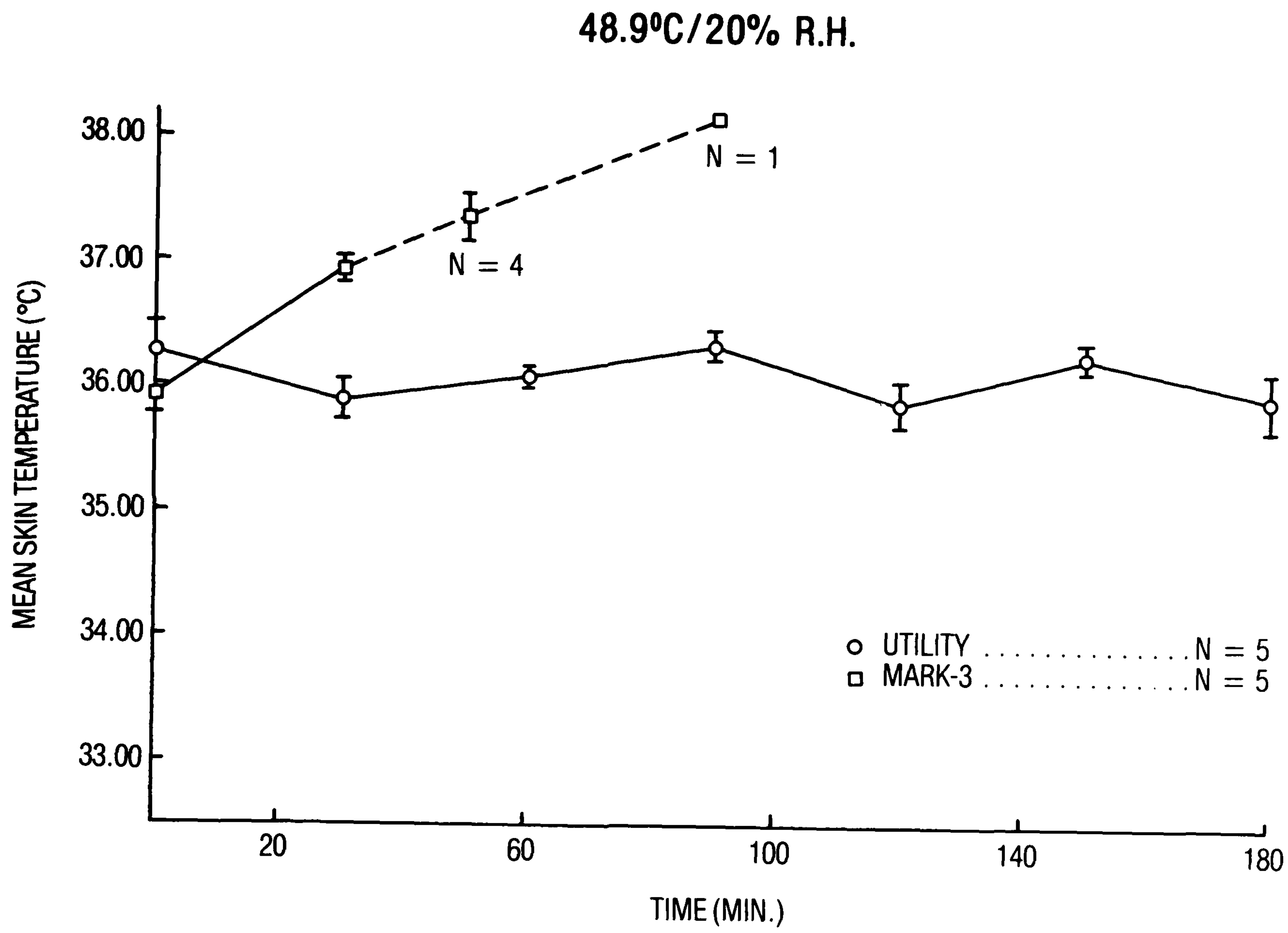

Figure 15. Half-hourly mean skin temperature values for each clothing ensemble tested at 48.9°C.

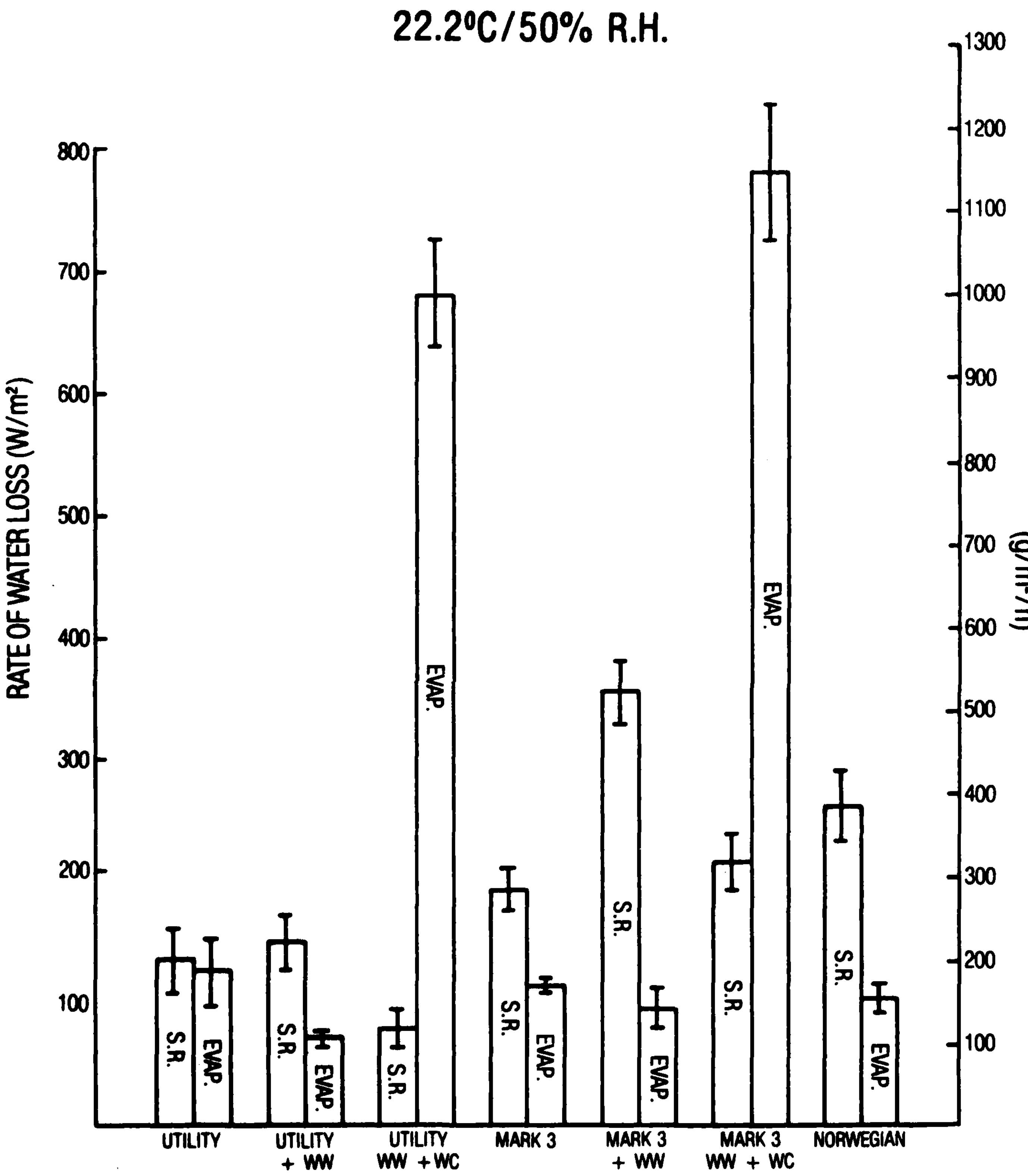

Figure 16. Rates of sweat (SR) and evaporation (EVAP) for each clothing ensemble tested at 22.2°C.

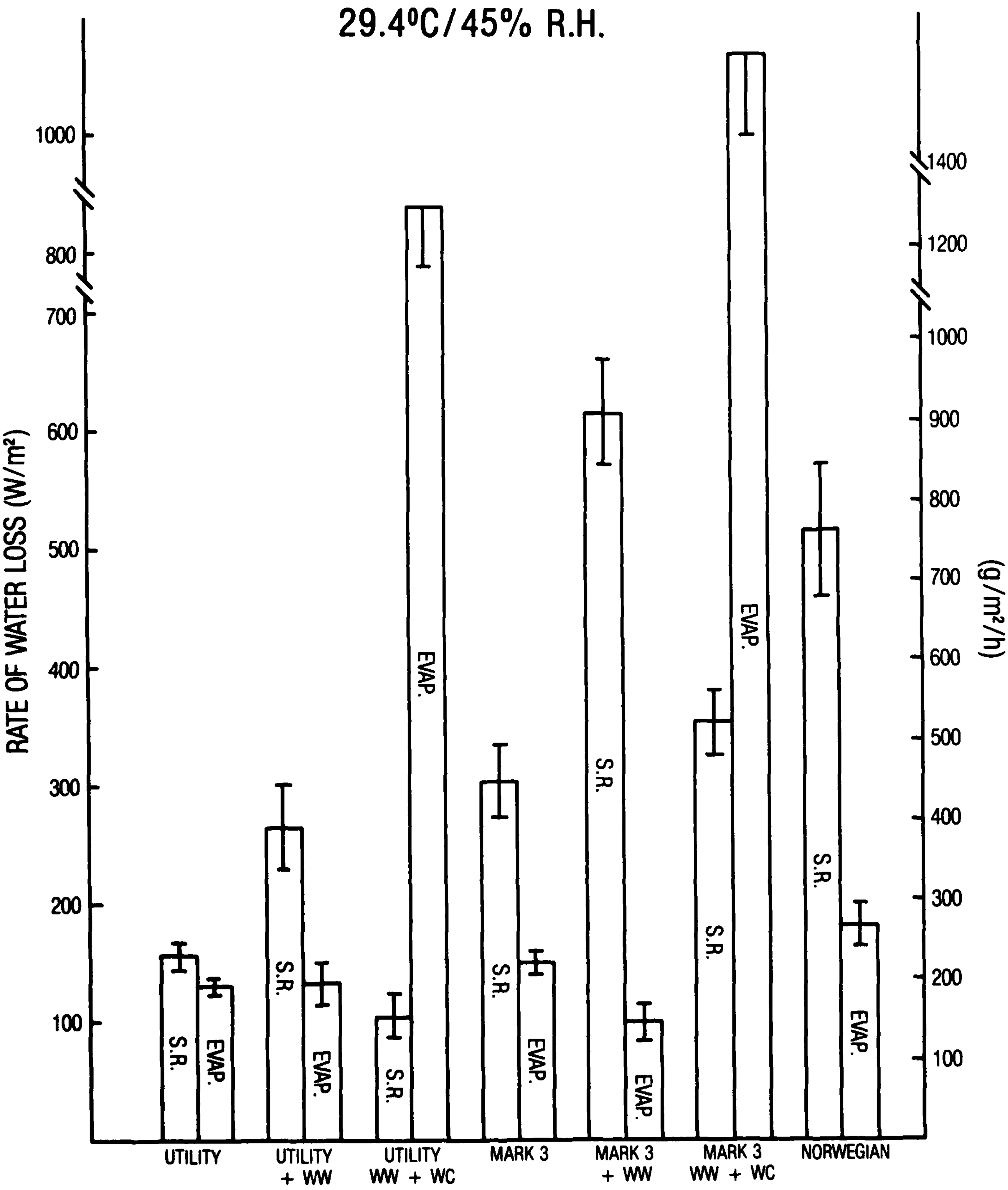

Figure 17. Rates of sweat (SR) and evaporation (EVAP) for each clothing ensemble tested at 29.4°C.

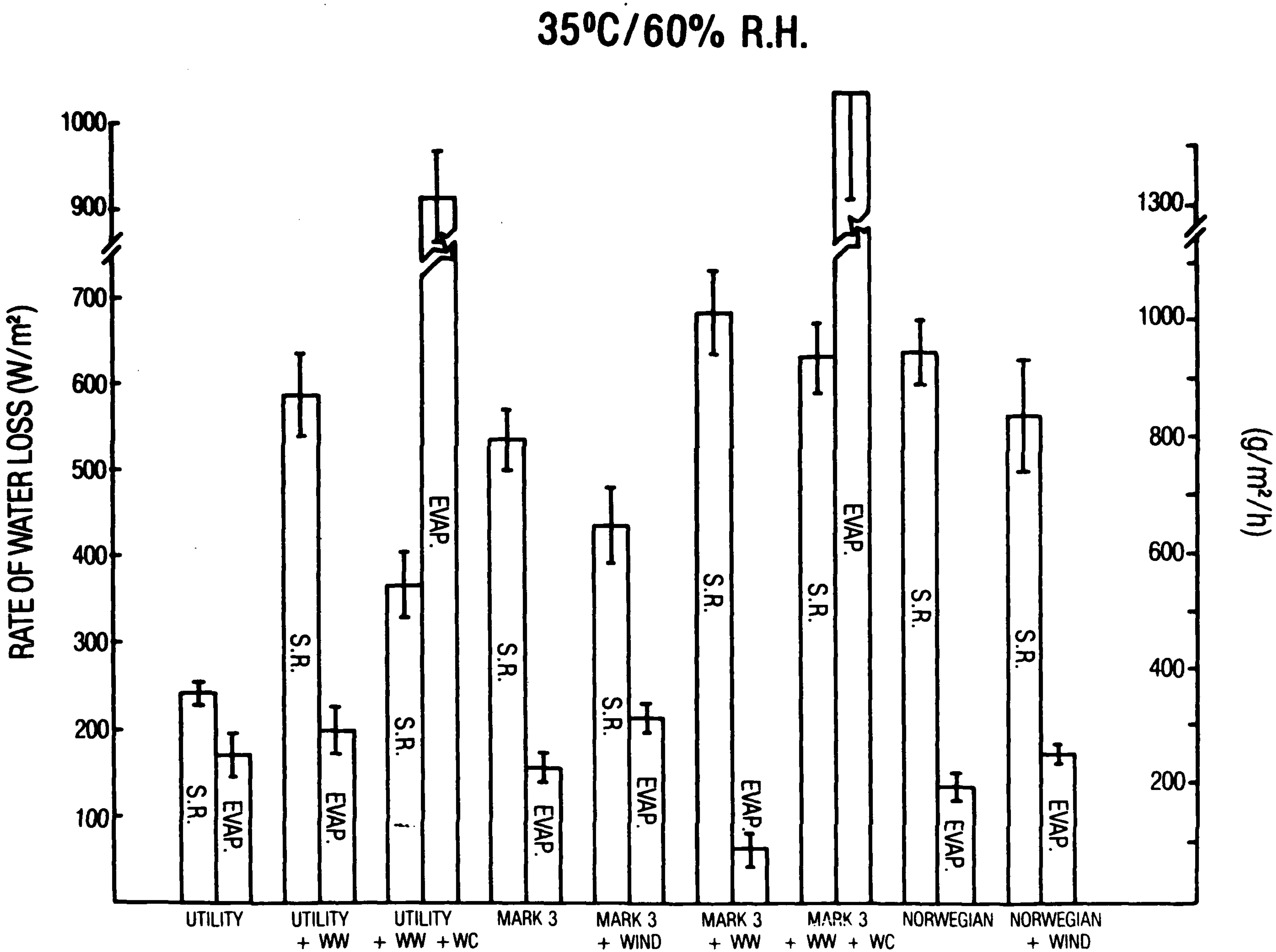

Figure 18. Rates of sweat (SR) and evaporation (EVAP) for each clothing ensemble tested at 35°C without and with wind.

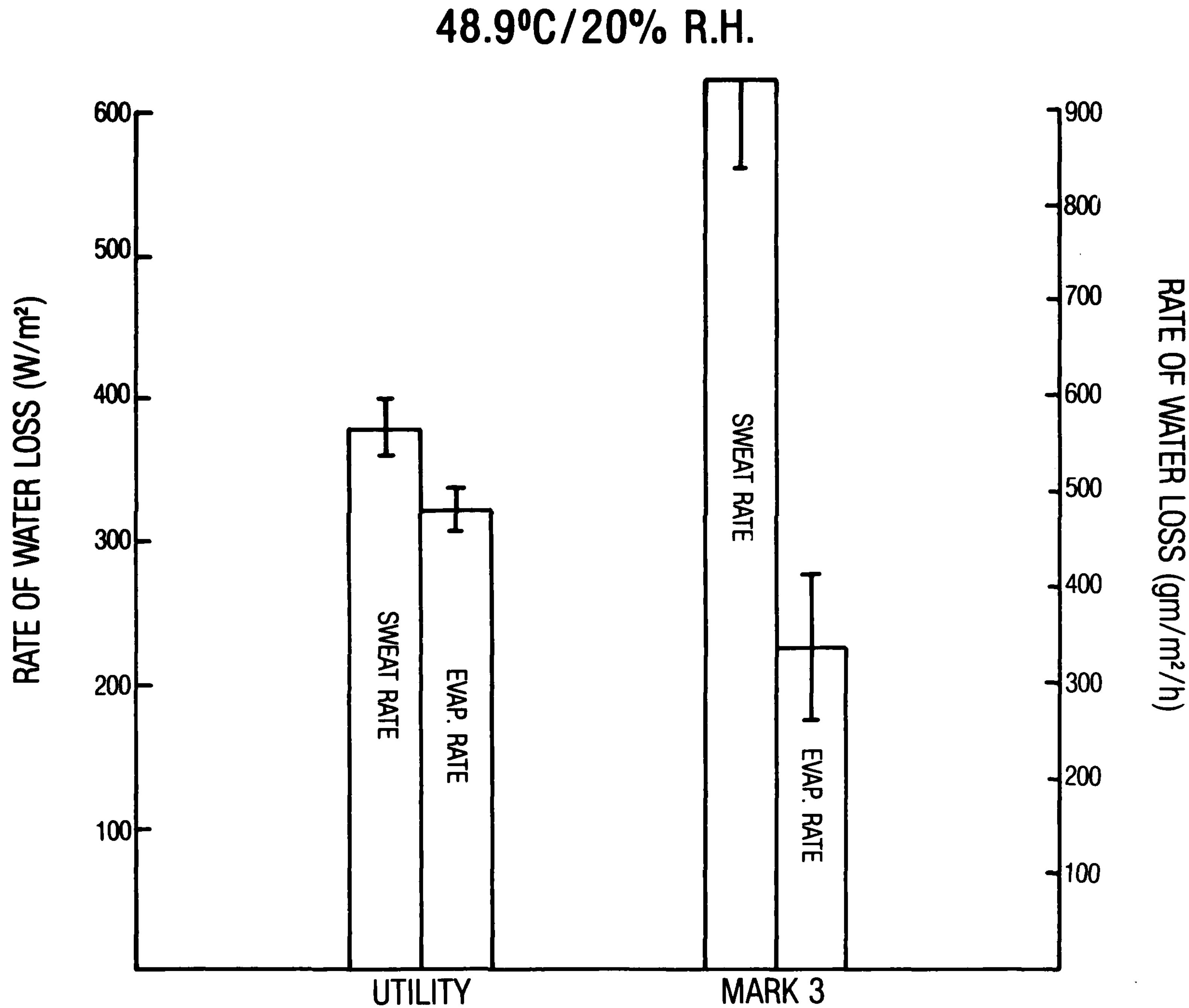

Figure 19. Rates of sweat (SR) and evaporation (EVAP) for each clothing ensemble tested at 48.9°C.

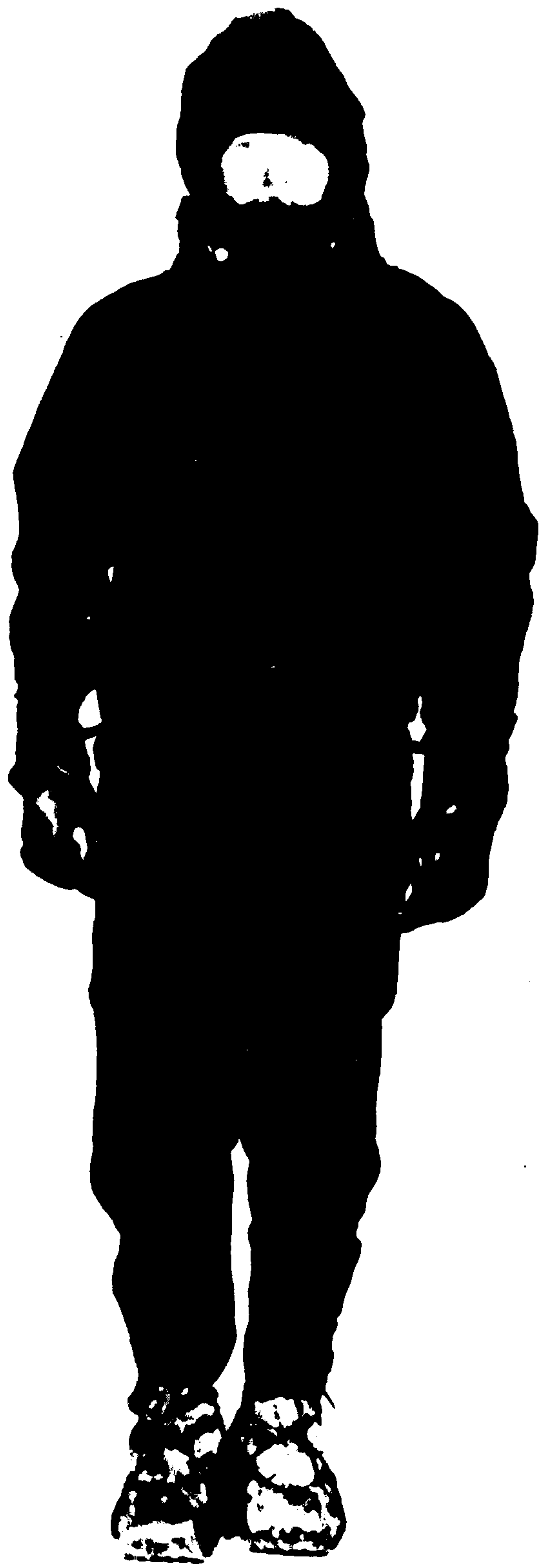

Figure 20. Mark III chemical protective uniform.

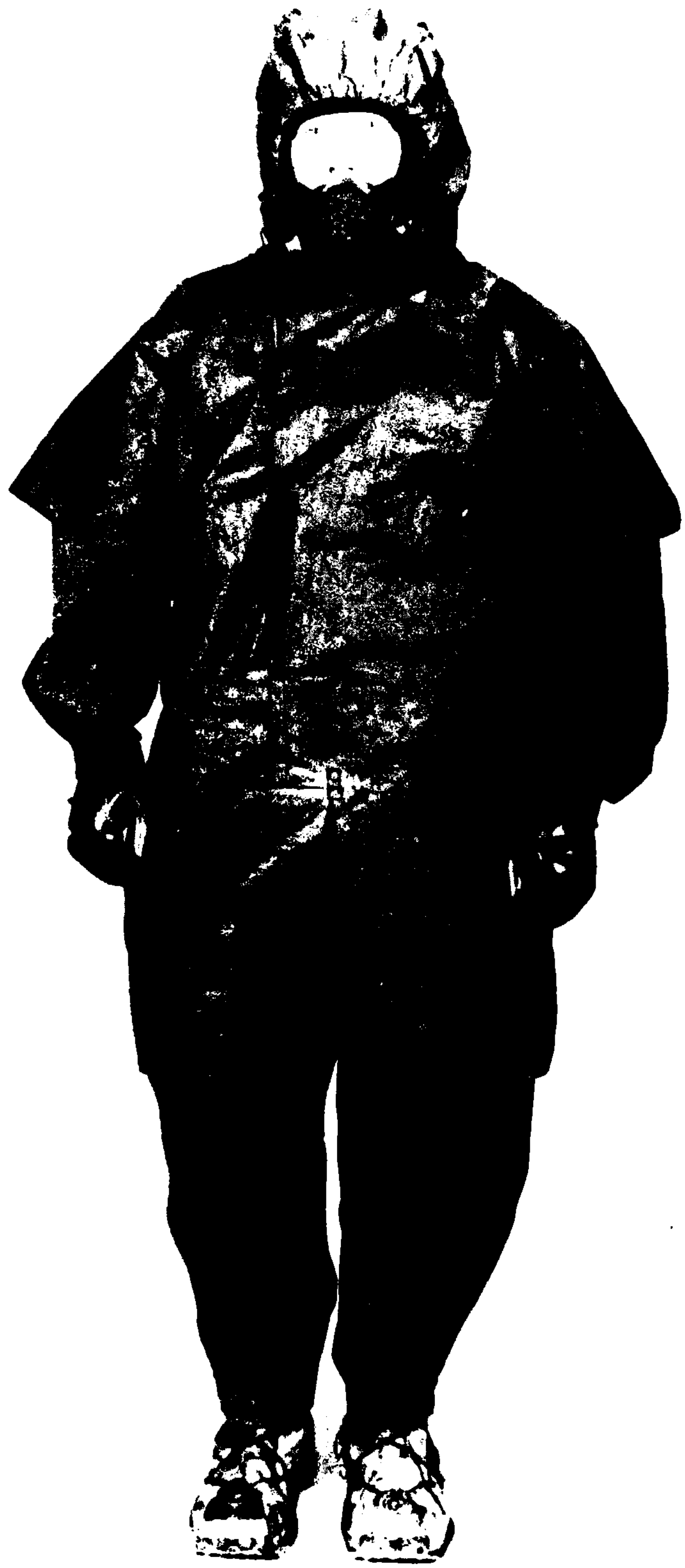

Figure 21. Norwegian Helly-Hansen chemical protective uniform.